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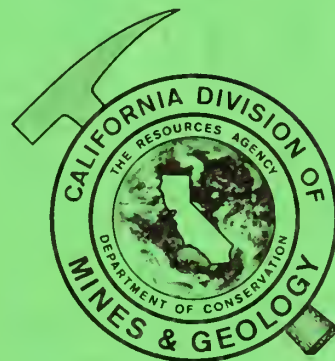
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MAMMOTH LAKES, CALIFORNIA EARTHQUAKES OF MAY 1980

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CALIFORNIA DIVISION OF MINES AND GEOLOGY

SPECIAL REPORT 150



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Special Report 150

MAMMOTH LAKES, CALIFORNIA
EARTHQUAKES OF MAY 1980

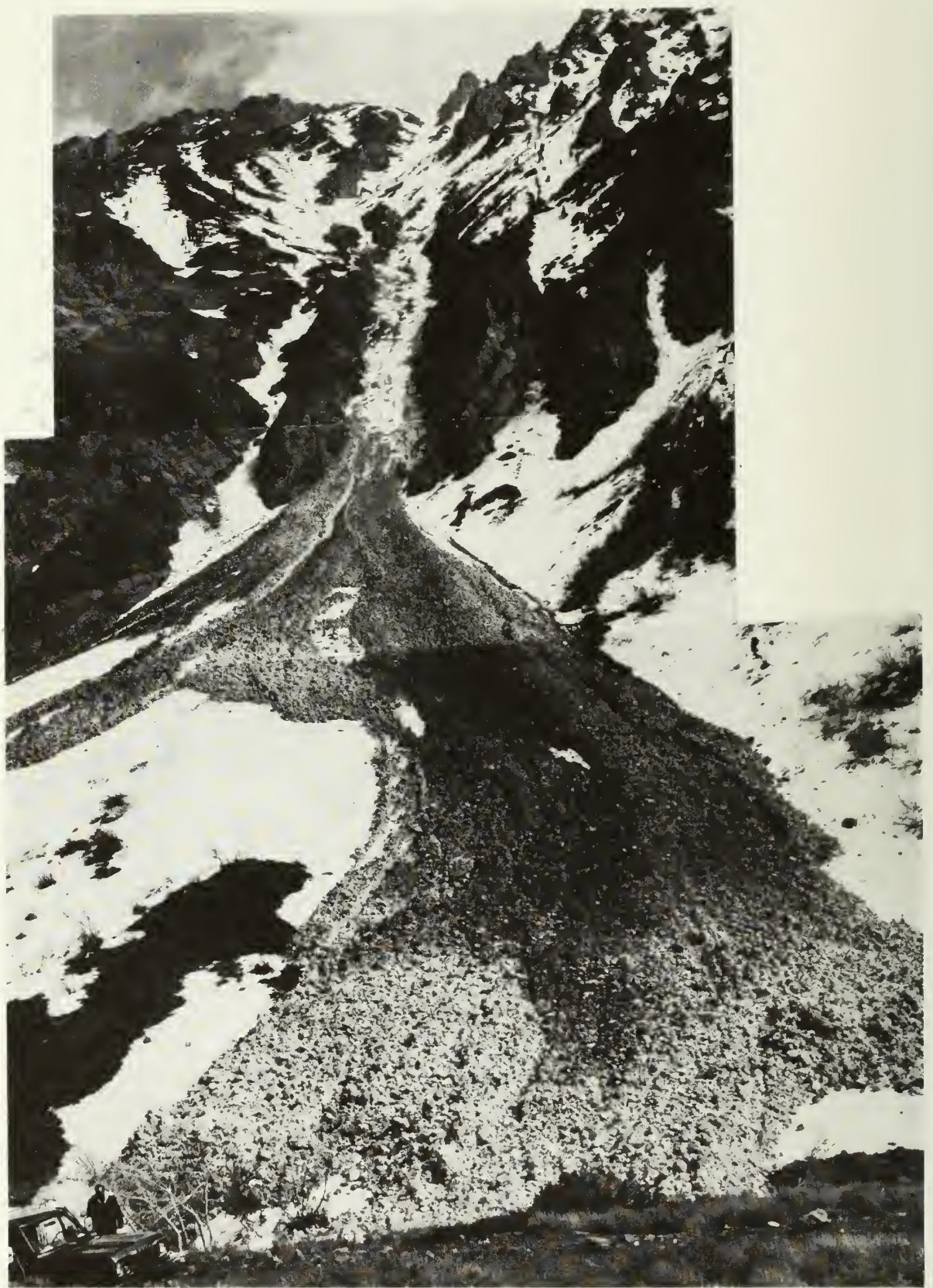
Edited by

Roger W. Sherburne

1980

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An avalanche of rock, snow, and ice in McGee Creek Canyon about 15 kilometers southeast of Mammoth Lakes was triggered by a magnitude 6.0 earthquake at 7:50 a.m. on May 27, 1980. This shock was the southernmost of the three largest earthquakes in the series. McGee Creek flows across the toe of the slide about 5 meters below road grade. Some of the debris at the toe of the slide in the foreground is more than one meter across. Because of the spectacular topographic relief in the area, rock-falls and avalanches posed an eminent hazard during the May 1980 Mammoth Lakes earthquake series.

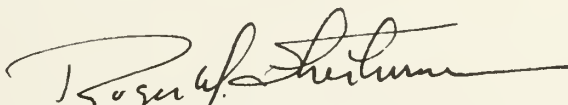
PREFACE

The eastern front of the Sierra Nevada Mountains is one of the more spectacular mountain areas within the contiguous United States. This scenic beauty has evolved as a result of a variety of geologic processes that have been operational for many millions of years, some of which remain active today. This special report contains information relative to some of those processes - but is concerned mainly with the very short lived (few seconds) geologic phenomena of earthquakes.

Beginning about September 1979, the earthquake activity in the Mammoth Lakes region, Mono County, California, intensified relative to the recent past. This unusual seismic activity consisted of numerous earthquake swarms, and culminated in four moderate earthquakes of about M 6, with numerous aftershocks of lesser magnitude during May 1980. This earthquake sequence represents the most significant earthquake activity to strike this region since the 1872 Owens Valley earthquake.

This special report contains eleven contributions presenting background information, and describing post-earthquake field programs and tentative results developed from these earthquake studies. Topics covered are related to the geologic, geodetic, and seismologic environment of the area, and the field programs conducted principally by the California Division of Mines and Geology staff following the 25 May 1980 M~6 events. Also included are two non-CDMG contributions, one from the University of California, Berkeley, and another from the University of Nevada, Reno. This special report is considered preliminary in scope because more data remains to be processed, and alternate interpretations are yet to be examined; the guideline for the preparation of this special report was "as soon as possible".

Efforts and cooperation of area residents were greatly appreciated; without their assistance many of the activities reported here would have been difficult if not impossible. The assistance of Fire Chief Jon Sweeny of Mammoth Lakes, California was fundamental to the success of the earthquake clearinghouse. The prompt and efficient cooperation of the California Office of Emergency Services and the California National Guard in arranging for and providing a helicopter overflight of the aftershock zone was very valuable to those earth scientists involved in studying the surface disruptions associated with the earthquakes.



Roger W. Sherburne
September 16, 1980

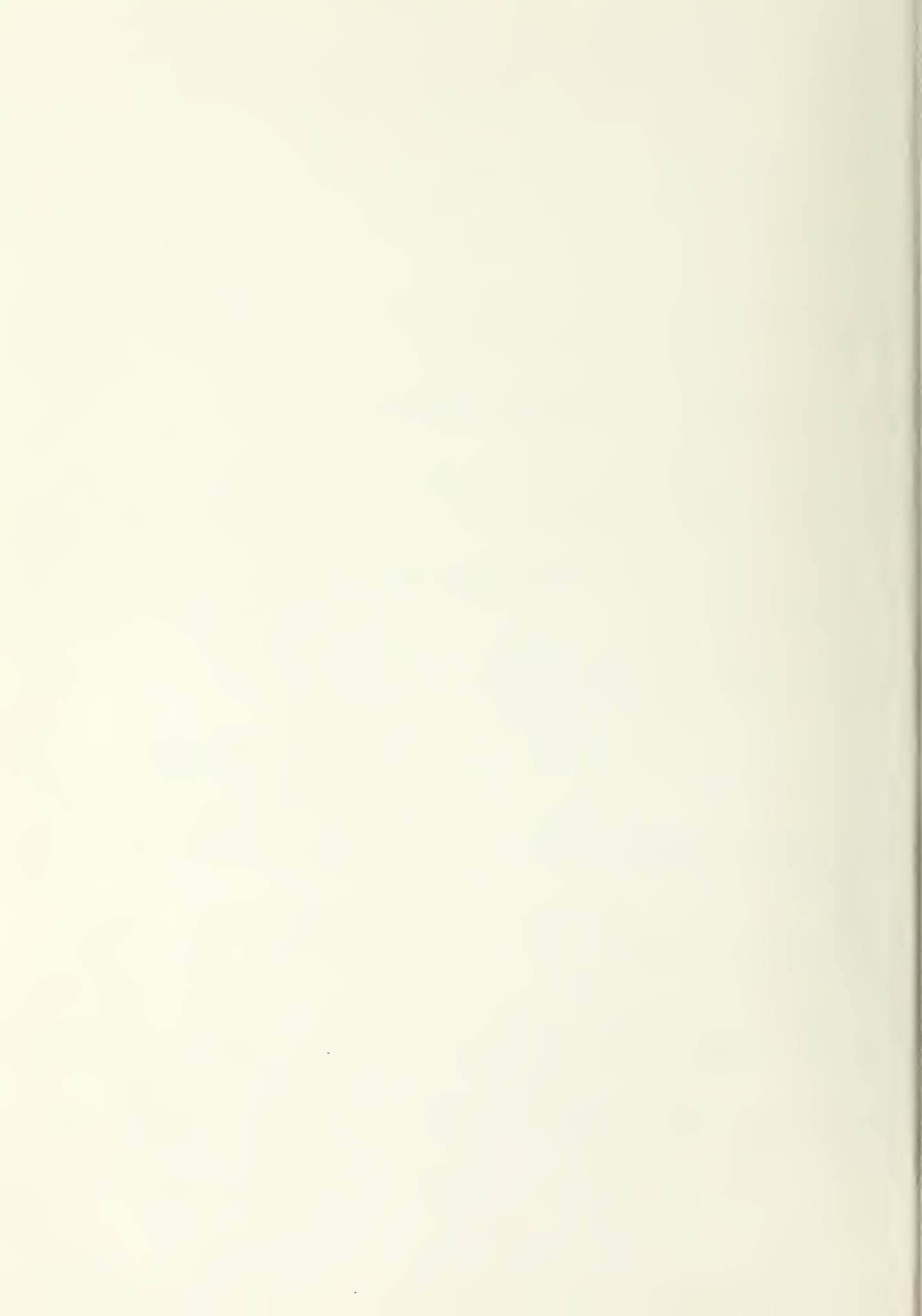


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REGIONAL GEOLOGY OF THE MAMMOTH LAKES REGION, CALIFORNIA

By

John T. Alfors
California Division of Mines and Geology

GEOLOGIC SETTING

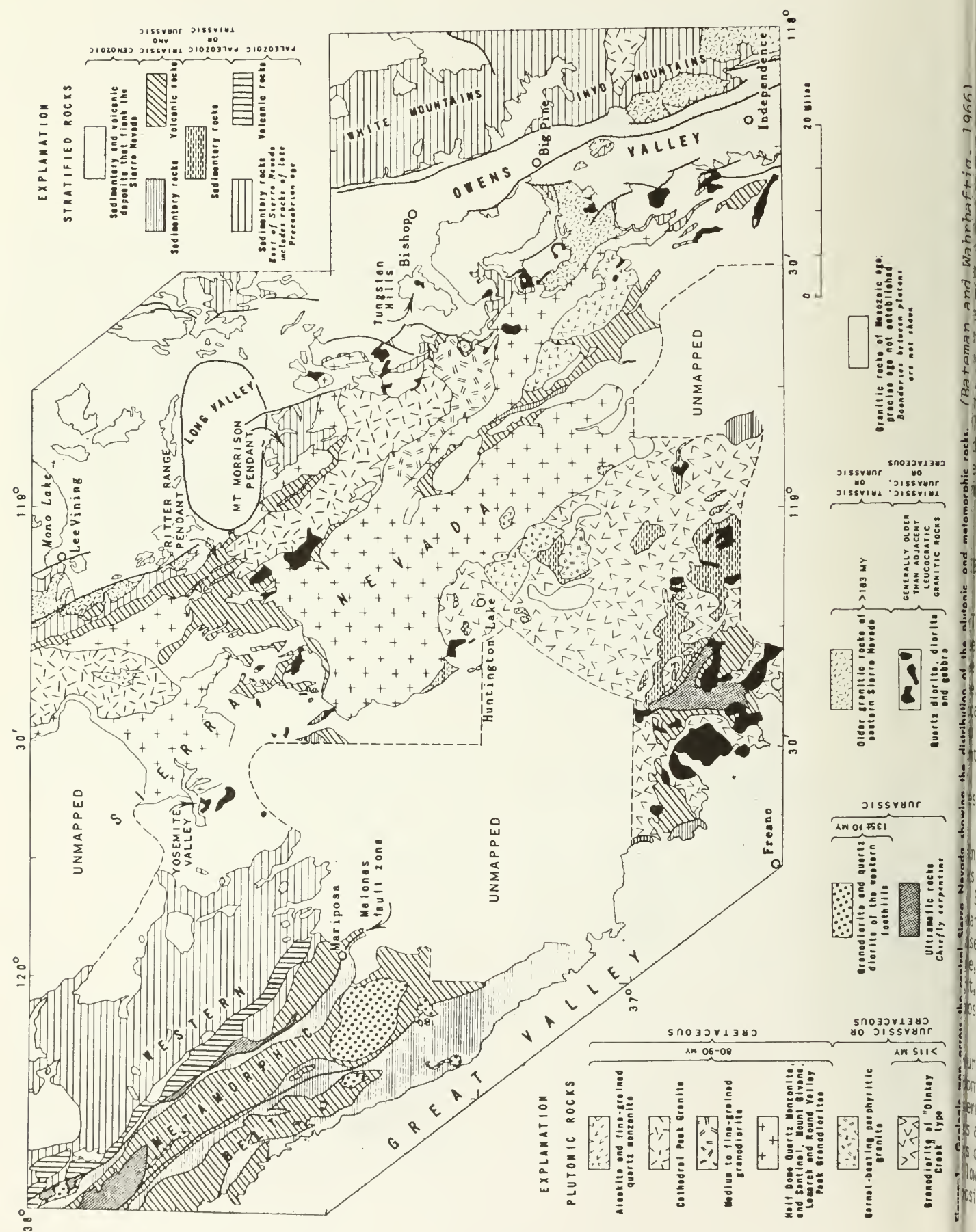
The Mammoth Lakes, California earthquakes of May 1980 occurred near the unincorporated town of Mammoth Lakes, Mono County at the base of the east front of the Sierra Nevada Mountains. The earthquakes occurred on faults which are part of the system of faults that form the boundary between the Sierra Nevada metamorphic province and the Great Basin metamorphic province. From the vicinity of Bishop (about 35 miles southwest of Mammoth Lakes) southward, the east frontal fault system is called the Sierra Nevada fault zone (Jennings, 1975). North of Bishop, the frontal fault system is less well-defined and is composed of a series of generally northwest-trending faults. Some of these individual fault segments are named, for example, the Hilton Creek fault, but most are unnamed (Jennings, 1975).

The Sierra Nevada is a huge block of the earth's crust, 400 miles long and 80 miles wide, that has broken free on the west along the Sierra Nevada fault system and been tilted westward. In the Mammoth Lakes region (roughly Lat. 37°N-38°N Long. 118°W-119°15'W), the Sierra Nevada is composed chiefly of Jurassic and Cretaceous granodiorites, quartz monzonites and granites of the Sierra Nevada batholith and Paleozoic and Mesozoic metamorphic rocks of the Mount Morrison and Ritter Range roof pendants (Bateman and Wahrhaftig, 1966, figure 1). Overlying the basement rocks on an erosion surface of moderate relief are late Tertiary volcanic rocks, mainly basalt, andesite, and rhyodacite (Bailey and others, 1976).

The Great Basin in California consists of high mountain blocks trending generally north-northwest separated by deep basins. In the Mammoth Lakes region, the high mountain blocks are represented by the White and Inyo Mountains and the deep basins by the northern extension of the Owens Valley trough. Bedrock units in this part of the Great Basin include later Precambrian sedimentary and metamorphic rocks, a thick section of Cambrian marine sedimentary rocks, Paleozoic marine sedimentary and metasedimentary rocks, Pre-Cretaceous metasedimentary and metavolcanic rocks, and Mesozoic granitic rocks. The bedrock units are unconformably overlain by Miocene to Holocene volcanic and sedimentary rocks (Strand, 1967).

GEOLOGIC LITERATURE

The Mammoth Lakes region has been the focus of a number of recent geologic studies. Some of these studies were part of a larger study of the tungsten-bearing and potential tungsten-bearing areas in east-central California (Bateman, 1965; Rinehart and Ross, 1964). Other studies have been directed to the geothermal areas of the region (Bailey and others, 1976; Bailey and Koeppen, 1977). Several are general geology studies (Huber and Rinehart, 1965; Kistler, 1966; Rinehart and Ross, 1957; Krauskopf and Bateman, 1977). Several recent studies have been directed toward analysis of the structural geology, volcanic history and recent crustal deformation of the region (Christensen, 1966; Gilbert and others, 1968; Pakiser, 1961; Pakiser and others, 1964; Wood, 1977; Crough and Thompson, 1977).



GEOLOGIC HISTORY

The geologic history of the Mammoth Lakes region is separable into four overlapping parts: (1) a long period in Precambrian and Paleozoic time when the area was mostly under the sea receiving sediments; (2) a shorter period during the Mesozoic when the Paleozoic strata were downwarped into a gigantic flexurally faulted synclinorium which was overlain with contemporaneous volcanic and metasedimentary detritus, strongly deformed, and intruded repeatedly by granitic masses, and eroded to a depth of 9 to 17 miles; (3) a period of relative stability in the late Cenozoic; and (4) a period of uplift, tilting, and faulting, preceded and accompanied by volcanic activity, in the late Cenozoic (Bateman and Haftig, 1966).

BATHOLITHIC GEOLOGY

The Mammoth Lakes region was mostly under the sea and receiving sediments from Precambrian time through Paleozoic time. More than 10,000 feet of late Precambrian and Early Cambrian age strata crop out along the west slope of the White Mountains (Bateman, 1965). These strata are mainly sandstone, siltstone, shale, limestone, and dolomite.

In the Sierra Nevada, metasedimentary rocks of probable Paleozoic age occur in the Bishop Creek pendant, Pine Creek pendant, and Mt. Morrison pendant. The metasedimentary rocks were derived from limestone, sandstone, siltstone, shale, and sediments of intermediate composition (Bateman, 1965).

During Mesozoic time, volcanic rocks intruded over sedimentary rocks in the region. The Mesozoic volcanic rocks are now represented by metavolcanic rocks derived from mafic flows, tuffs, and dikes, and intrusives of andesitic to dacitic composition (Bateman, 1965).

BATHOLITHS

The emplacement of Mesozoic batholithic rocks in the Mammoth Lakes region and adjoining parts of the Sierra Nevada was accomplished during five major pulses of deformation and intrusion (Evernden and Kistler, 1970). Granitic rocks of the Lee Vining intrusive epoch of Early or Middle Triassic age are the oldest in the region with geochronologic dates of 210 m.y. to 195 m.y. ago. These granodiorites and quartz monzonites are exposed in a series of relatively small separated outcrops from the vicinity of Mono Lake to a short distance south of Bishop.

The second oldest batholithic rocks in the region are granitic rocks of the Inyo Mountains intrusive epoch of Early and Middle Jurassic age with geochronologic dates of 180 m.y. to 160 m.y. ago. In addition to the majority of the plutonic rocks exposed in Inyo and White Mountains, the Tinemaha granodiorite, which crops out in the Sierra Nevada south of Bishop, belongs to this intrusive epoch.

Granitic rocks of the Yosemite intrusive epoch of Late Jurassic age have geochronologic dates of 148 m.y. to 132 m.y. ago. They are exposed in the Yosemite Valley area and form an extensive northwest-trending zone along the western foothills of the northern Sierra Nevada.

Early Cretaceous age granitic rocks of the Huntington Lake intrusive epoch have geochronologic dates of 121 m.y. to 104 m.y. ago. These rocks, ranging from quartz diorite, granodiorite, to quartz monzonite in composition, crop out along the western foothills of the southern Sierra Nevada generally south of Yosemite Valley.

The youngest batholithic rocks in the Sierra Nevada are granitic rocks of the Cathedral Range intrusive epoch of Late Cretaceous age that have geochronologic dates of 90 m.y. to 79 m.y. ago. These rocks range from granodiorite to granite in composition and generally occupy the crestal regions of the Sierra Nevada along its entire length.

CENOZOIC ROCKS

The oldest Cenozoic rocks of the Mammoth Lakes region are andesite, dacite, rhyolite and welded tuff units exposed north and east of Mono Lake. These rocks have been radiometrically dated as 11 to 29 m.y. old and are thus late Oligocene and Miocene in age (Silverman and others, 1972).

The Pliocene (the time between 3 and 12 m.y. ago) is represented by isolated outcrops of rhyolite, andesite, basalt, and pyroclastic rocks in the Sierra Nevada, the White Mountains, and the intervening lowland (Strand, 1967). These volcanic rocks have radiometric ages of 12 to 7.5 m.y. ago and 4.5 to 3 m.y. ago (Gilbert and others, 1968). The period between 7.5 and 4.5 m.y. ago was a time of little or no volcanic activity in the Mammoth Lakes region.

The Pleistocene is represented by extensive deposits of volcanic and sedimentary rocks. Most of these deposits are located in the trough area between the Sierra Nevada and the White Mountains (Strand, 1967). Volcanism in this area occurred almost continuously through the Pleistocene to the recent. A major Pleistocene volcanic event was the eruption of the Bishop Tuff about 700,000 years ago. The Long Valley caldera was formed as a direct result of this eruption and intracaldera volcanism has continued to recent times (Bailey and others, 1976). Holocene volcanism has occurred throughout the Mono Basin-Long Valley area. During the past 2000 years, at least 30 volcanic events have been documented (Kilbourne and others, 1980).

GEOLOGIC STRUCTURE

Several periods of regional deformation, consisting of combined folding, faulting, cataclasis, and regional metamorphism occurred throughout the Mammoth Lakes region during Paleozoic and Mesozoic time (Nokleberg and Kistler, 1980). The oldest regional deformation

occurred along northward trends during Devonian and Mississippian periods. mountain chain rose during Mississippian in about the same area the present southern Sierra Nevada (Stewart and Ross, 1966). This mountain chain extended into central Nevada with the orogenic event that produced the chain is referred to as the Antler orogeny.

A Late Permian regional deformation consisting of uplift, erosion, and onset of Andean-type volcanism is expressed as an angular unconformity exposed from the Saddlebag roof pendant (west of Mono Lake) south to the Mount Morrison roof pendant (Nokleberg and Kistler, 1980). This orogenic event is referred to as the Sonoma orogeny in Nevada (Stewart and Ross, 1966).

A Triassic deformation occurred along N20°-40°W trends and is defined by folding and faulting of Permian and Triassic metavolcanic rocks of the Saddlebag Lake and northern Ritter Range roof pendants, and of Pennsylvanian and Permian (?) metasedimentary rocks of the Pine Creek roof pendants (Nokleberg and Kistler, 1980).

An Early and Middle Jurassic deformation is defined by an angular unconformity in the Mount Dana area east of Mono Lake (Nokleberg and Kistler, 1980). In the western foothills of the Sierra Nevada, the upper Paleozoic Calaveras Formation is intensely deformed by the orogeny along N30°-60°E trends.

The Late Jurassic Nevadan orogeny affected large areas of the Sierra Nevada including the Ritter Range and Mount Morrison roof pendants in the Mammoth Lakes region. The most intense deformation occurred in the western foothills of the Sierra Nevada as a fault-fold system, striking N20°W (Nokleberg and Kistler, 1980).

A period of intense folding, cataclasis, and regional metamorphism along N 50°-80°W trends occurred during the Early or early Late Cretaceous. Several widely separated roof pendants

cluding the Ritter Range, Mount Morrison, Saddlebag Lake, Mount Dana, and Bishop Creek roof pendants (Nokleberg and Stetler, 1980).

During the Tertiary, thick continental deposits were laid down in local basins and volcanic activity was widespread. In the latter part of the Tertiary, the physiographic features--the basins and ranges--began to take the shape we see today. High-angle faulting was dominant, uplifting mountain blocks and defining the compressed basin areas (Stewart and Ross, 1966). Mono Basin developed during the last 3-4 m.y. as a result of regional unroofing and faulting, with volcanism perhaps related but playing a minor role (Christensen and others, 1969). Long Valley caldera, a 17- by 32-km elliptical depression on the east front of the Sierra Nevada, formed 0.7 m.y. ago during eruption of the Bishop tuff (Bailey, Dalrymple and Lanphere, 1976). The Sierra Nevada frontal fault system cuts Pleistocene-aged moraines at a number of localities indicating post-Pleistocene movement.

Regional deformation, faulting, and volcanism has continued in the Mammoth Lakes area to the present time. Active hot springs and fumaroles are located along many of the north to northwest-trending faults (Rinehart and others, 1964). In 1872, one of the largest historic earthquakes in the United States shook Owens Valley (just south of the Mammoth Lakes region) and caused extensive surface faulting and ground rupturing along the Sierra Nevada fault zone for a distance of nearly 100 km (Oakeshott, Mansfield, and Kahle, 1972). The May 1980 earthquakes are the latest evidence of the continuing tectonic movements along the east front of the Sierra Nevada.

ACKNOWLEDGMENTS

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RECENT VOLCANISM IN THE MONO BASIN-LONG VALLEY REGION OF
MONO COUNTY, CALIFORNIA

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ABSTRACT

Obsidian hydration rind and C^{14} age dating, has shown the recent volcanic history of the Mono Basin-Long Valley region to consist of at least 30 tephra and lava eruptions during the past 2000 years. The physical and chemical characteristics of the lava suggest multiple local magma sources possibly derived from a single parent magma. The mechanism for eruption would appear to include: (1) Earthquakes along the Sierra Nevada Frontal fault system which open fissures or lessen the horizontal confining pressure along faults reaching the magma chamber, (2) viscous siliceous magma rises towards surface along these weakened fractures; at the same time groundwater may leak downward, (3) when contact is made a steam explosion displaces pre-existing volcanic and lacustrine sediments forming a crater, (4) if magma continues to rise, eruptions continue, changing in character from phreatic (steam) to phreatomagmatic and eventually magmatic with the formation of a new dome. The process stops whenever the magma cools enough to congeal and seal that portion of the fissure. Support for this mechanism is found in the examination of the physical and chemical character-

istics of the Mono-Inyo Craters chain of eruptive centers and the chronological sequence of dated eruptions.

Intracontinental volcanic eruptions have not been as numerous nor have precursory phenomena been as well documented as plate boundary and oceanic volcanoes such as the Cascades, and those in Iceland, Japan and Hawaii. Precursory phenomena that might accompany the Mono Basin-Long Valley mode of eruption could include volcanic earthquakes (of A and B type as described by Minakami, 1974); explosion and perhaps harmonic tremors; abnormal changes in groundwater levels; increases in temperatures of groundwater and/or hot springs; chemical changes in hot springs and fumarolic gases; and minor phreatic explosions. Volcanic terminology used in this paper is after Macdonald (1972).

INTRODUCTION

As a result of the current Mammoth Lakes earthquake swarm, much interest has been generated concerning a possible relationship between these earthquakes and the recent volcanism in the Mono Basin-Long Valley region. This region (figure 1) is one of four in California for

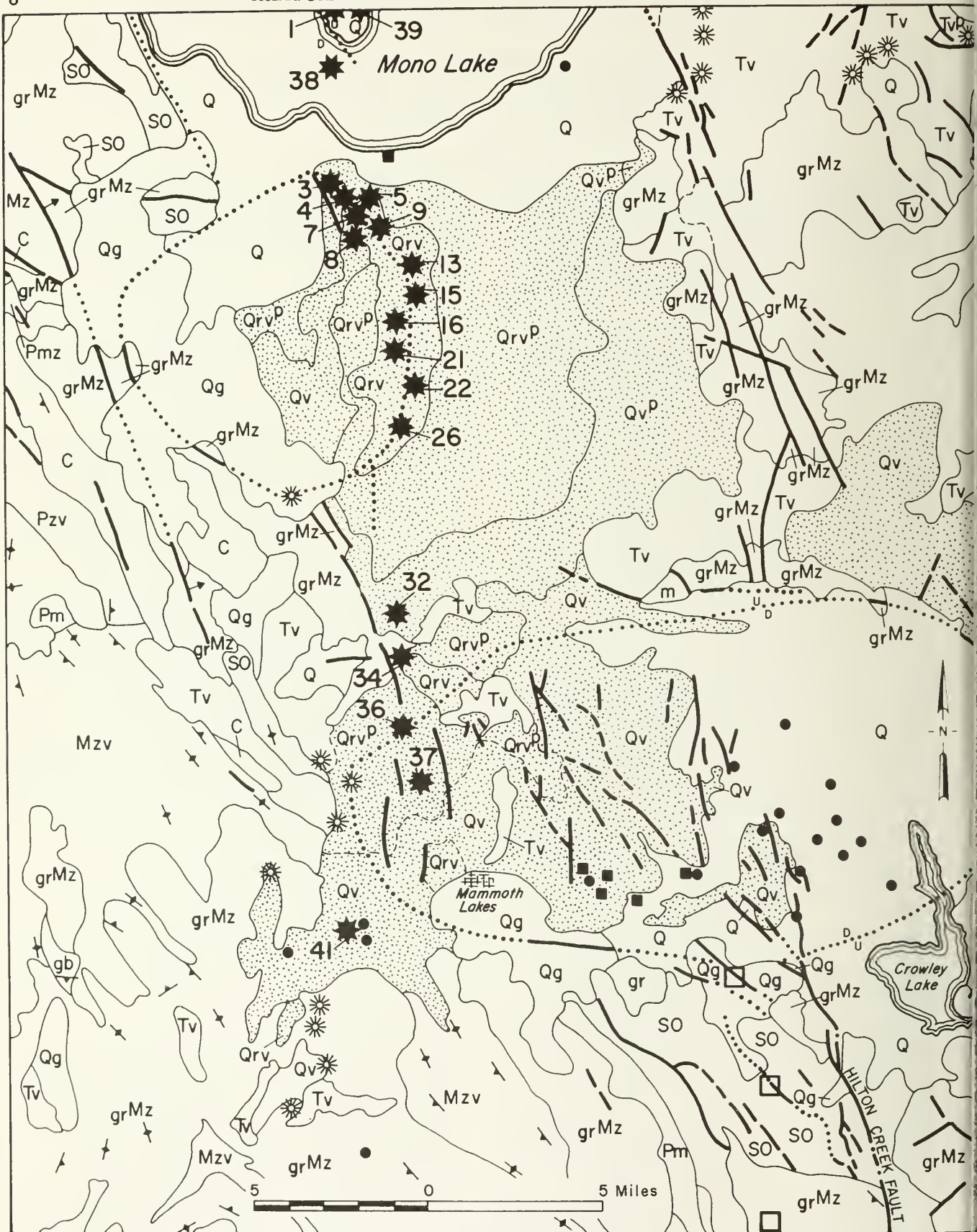


Figure 1. GEOLOGIC MAP OF STUDY AREA. Quaternary volcanic rocks are shaded; most are probably Holocene in age. ★ = eruptive center dated as younger than 2000 years. Number refers to eruptions listed in Table 2; * = other Quaternary eruptive centers; ● = thermal spring location; ■ = thermal well location; □ = epicenters of the three $M \geq 6.0$ shocks of 1980 Mammoth Lakes earthquake swarm. Other symbols are as on source map (Jennings, 1977).

h there is well-documented evidence multiple volcanic eruptions in the two millenia. The Cascade Range s, Mt. Shasta and Mt. Lassen and the Pine Lake Highlands (Glass Mountain- le Glass Mountain) are the other e.

urrent understanding of the tectonic ework of the Western United States ests that the volcanism in the Basin Range Province, which includes the ect area, is unrelated to the develop- of the volcanoes of the Cascade Range.

e Cascades are calc-alkaline volcanoes volcanic arc associated with the rgence of the downgoing (subducted) uan de Fuca oceanic plate and the iding North American continental . The Cenozoic Great Basin volcanic nce, on the other hand, has produced ly a bimodal rhyolite-basalt suite. ts are typically alkali rich (Leeman ogers, 1970). Late Cenozoic volcanism ormal faulting has been concentrated rrow zones distributed near the ns of the Great Basin (Christiansen cKee, 1978). The Sierra Frontal zone and the volcanism in the Basin, Long Valley, and the Coso are within one of these zones. The a Frontal fault system is apparently enough to provide conduits to magma ould be an agent of the volcanism.

is article on recent volcanism in the Basin-Long Valley region will address subject of the potential for future aic activity by presenting (1) a ation of the dates of occurrence e most recent eruptions and estimates es of volcanics using the technique tidian hydration rind dating, (2) a ive history, in chronological order canism during the past 2000 years, ggestions of possible mechanisms of itiation of an eruptive episode in ea, and (4) suggestions for monitor- recursory activity.

is important at the beginning to e that this is not an assessment of volcanic hazards. The numerous recent

volcanic deposits in the area have not been adequately or systematically studied to identify the nature of damage and devastation associated with these deposits of past eruptions so that we may forecast the kinds of hazards we may expect in the future from these volcanoes. The May 18, 1980 eruption of Mount St. Helens shows that a moderate-to-large-volume eruption in an area of relatively low population density can create a significant and costly disaster (Hammond, 1980, University of Washington Geophysics Program, 1980, and Christiansen, 1980). A useful ranking of the size and severity of past volcanic eruptions generally relates to the volume of erupted tephra where 0.01, 0.1, and 1.0 km³ represent minor, moderate, and large volumes (Crandell and Mullineaux, 1978). Several eruptions in the Mono and Inyo chain in the last two millenia have been at least moderate in volume by this scale (Wood, 1977a). A number of recent and late Quaternary deposits give evidence that volcanoes in this area are capable of potentially dangerous events such as hot pyroclastic flows, block and ash avalanches, pyroclastic surges, and major tephra falls (Wood, 1977a, 1977b, and Lipshie, 1976), and rock avalanches (Bailey and Koeppen, 1977). Directed blasts and hazards due to volcanic gases are also possible and have been documented elsewhere (Christiansen, 1980, Gorshkov and Dubik, 1970, Gorshkov, 1969, and Wilcox, 1959). We do not have, however, any data regarding the pre-historic occurrence of these hazards in the Mono Basin-Long Valley region.

No discussion of this area would be complete without mention of the gigantic eruption that led to the formation of the Long Valley Caldera and the widespread Bishop Tuff about 700,000 years ago. Total volume of rhyolite magma ejected was of the order of 600 km³ (Bailey *et al.*, 1976). Such eruptions are infrequent and none have occurred during the written history of mankind. The geologic history of the Long Valley area prior to the Bishop Tuff eruption bears several similarities to recent volcanism of the Mono chain, and Bailey (USGS, 1976) has

suggested that the Mono chain might be in the early stages of caldera evolution.

The article is intended to give a timely and realistic appraisal of the likelihood of future eruptions in the region. It is recognized that this is not, and should not be, the final work on this subject. Further field oriented studies are now being carried out by the U.S. Geological Survey (Meyer Rubin, 1980, personal communication); and the California Division of Mines and Geology is monitoring seismic activity in the subject area (see other articles in this publication).

GEOLOGY

Regional Geologic Framework

Relation to Basin and Range Province and plate tectonics. The subject area lies on the east side of the Sierra Nevada, near the western margin of the Basin and Range province (figure 2). This province is characterized by narrow, fault-bounded, generally northerly trending mountain ranges separated by irregular alluvium-covered valleys; it is believed to have developed since mid-Cenozoic time largely through extensional deformation coincidental with the development of the San Andreas transform (Dickinson, 1979, Coney, 1978).

The province, especially that portion between the eastward extensions of the Mendocino and Murray fracture zones, is considered a slab-free region (Proffett, 1977) in which perhaps an upwelling of the asthenosphere replaced the descending lithosphere to produce late Tertiary and Quaternary magmatic and volcanic cycles (Dickinson, 1979). Figure 3 illustrates this concept.

Christensen (1966) concludes the present elevation and tilted west slope of the Sierra are the result of broad upwarping involving also the Basin-Range province during a period between 9 and 3 million years ago. Available evidence suggests major downfaulting that created the eastern escarpment did not begin until the Pleisto-

cene. The frontal fault system of the eastern Sierra escarpment cuts Wisconsin aged moraines at the mouths of a number of canyons (Chesterman, 1975). Activity along this frontal fault system continues today and the May, 1980 earthquakes have caused surface offset along the Hilton Creek fault.

Recent volcanism in the subject area is centered about the islands of Mono Lake, and the Mono and Inyo Craters and domes that comprise a chain of late Quaternary domes, flows, craters, and pyroclastic deposits that extends about 35 km southward from Mono Lake to the Mammoth Mountain volcano (Photo 1). Most of the recent volcanoes of the chain are principally rhyolite and rhyodacite in composition. According to Kistler (1966) the rocks beneath the Mono Craters are basalt and probably the basalt of June Lake Junction which was emplaced between advances of Tioga and Tahoe glaciers (Putnam, 1938). Rocks beneath the Inyo Crater include Quaternary basalt and andesite flows and late Quaternary pyroclastic deposits. Basement rock beneath the volcanics are Mesozoic plutonic and metamorphic rocks (Rinehart and Ross, 1964, and Kistler, 1966).

Characteristics of Recent Eruptions

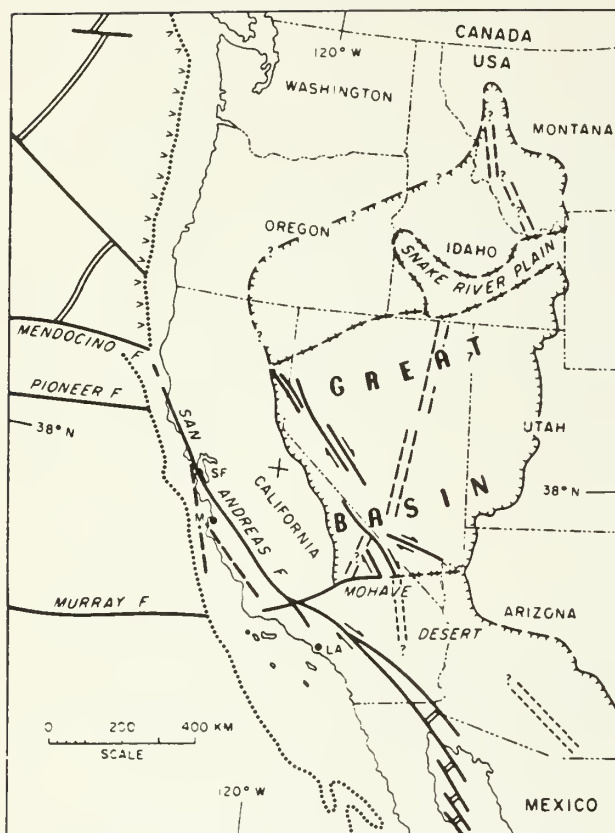
Chemistry of rocks. The Mono and Inyo chain of volcanic events are a series of craters, tephra, cones, domes, flows. The volcanic rocks range from rhyolite to rhyodacite in composition, but most are rhyolitic (Table 1). Eruptions in the Mono Basin-Long Valley area in the last 30-40,000 years (Wood, 1977a) have produced rocks that range in composition from dacite to rhyolite, with the bulk of them being rhyolite. The oldest feature is a dome of rhyodacite on the northwest side of Mono Craters. This rock is medium gray, contains large phenocrysts of andesine and sub-angular inclusions of dark reddish-gray andesite. Negit Island in Mono Lake consists of rhyodacite flows and a cinder cone. Paoha Island (figure 4) is a more recent rhyolite dome with the northeast corner

TABLE 1: CHEMICAL ANALYSIS OF RECENT VOLCANIC ROCK

	1	2	3	4	5
SiO ₂	73.26	72.08	67.28	74.5	74.1
TiO ₂	0.13	0.16	0.35	0.09	0.13
Al ₂ O ₃	13.41	14.02	15.29	12.7	13.05
Fe ₂ O ₃	1.49	1.83	1.86	1.2	1.5
Mg	0.03	0.00	0.22	0.0	0.0
Mn	0.06	0.06	0.13	0.05	0.06
CaO	0.73	0.81	0.77	0.59	0.78
Na ₂ O	3.94	4.20	4.71	3.8	4.15
K ₂ O	4.93	5.06	4.76	4.6	4.6
P ₂ O ₅	0.01	0.01	0.04	0.00	0.01
Sr	0.0022	0.0040	0.0081	-----	-----
Rb	0.0151	0.0152	0.0104	-----	-----
Zr	0.0143	0.0185	0.0290	-----	-----
Loss	0.00	0.00	0.00	-----	-----
Total	97.99	98.23	95.41	97.53	98.38

1. Pumiceous aphyric rhyolite. Dome immediately south of Deadman Creek, Mono County, California (Wood, 1977b).
2. Pumiceous aphyric rhyolite. Cratered dome on Glass Creek, Mono County, California (Wood, 1977b).
3. Pumiceous porphyritic pumice. Airfall tephra exposed in roadcut adjacent to Highway U.S.S. 395, SW 1/4, Sec. 1, T3S, R27E, MDM, Mono County, California (Wood, 1977b).
4. Porphyritic glassy rhyolite. Small dome on northwest side of Northwest Coulee, NW 1/4 Sec. 30, T1N, R27E, MDM, Mono County, California (Wood, 1977b).
5. Porphyritic glassy rhyolite. Dome on southeast side of Crater Mountain, Mono County, California (Wood, 1977b).

Note: All analyses by XRF except for Na₂O, which was by INAA. All Fe is reported as Fe₂O₃. Iron reported as FeO would diminish total iron. Water probably accounts for most of the missing component since published analyses of comparable rocks from the Mono Craters show water in amounts ranging from 0.8 to 2 percent. Analyses by G. Cunningham, Center for Volcanology, University of Oregon.



- CONTINENTAL MARGIN
- CONTINENT MARGIN UNDERTHRUST BY SEA FLOOR
- BOUNDARY OF BASIN AND RANGE PROVINCE
- BOUNDARY BETWEEN DIFFERENT PARTS OF BASIN AND RANGE PROVINCE
- ===== OCEANIC SPREADING AXIS
- ===== ACTIVE AXIS OF BASIN AND RANGE SPREADING
- ===== INACTIVE AXIS OF BASIN AND RANGE SPREADING
- ===== SEA FLOOR FRACTURES AND MAJOR STRIKE-SLIP FAULTS SHOWING DIRECTION OF DISPLACEMENT

Figure 2. Generalized tectonic map of western United States and adjacent sea floor, showing approximate axes of crude symmetry of broad zones of spreading. SF=San Francisco; M=Monterey; LA=Los Angeles. (Modified after Proffett, 1977).

overlain by a rhyodacite flow and cinder cones (Lajoie, 1968).

The lavas and pyroclastic materials at most of the eruptive centers are glassy, and range from dark obsidian through various degrees of vesicularity

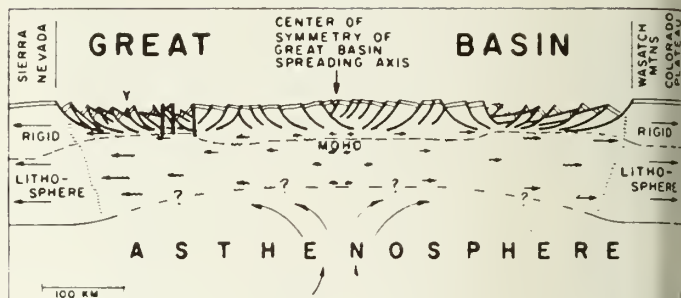


Figure 3. East-west cross section of the Basin and Range Province, showing diagrammatically crude symmetry of the Basin and Range faulting and possible movement of material at depth. Antithetic faults are not shown, but they could be present in place of at least part of the tilting in some areas. (Modified after Proffett, 1977).

to white pumice whose bulk specific gravity is less than 1; their density ranges from 0.51 to 0.78 g per cc (Loney 1968). Rocks erupted from the centers prior to about 3,000 B.P. are sparsely porphyritic, with 3 to 10 percent microphenocrysts of sanidine, whereas rocks erupted since that date are aphyric rhyolite, more or less devoid of microphenocrysts (Wood, 1977b). Excepting for the older rhyodacite dome on the northwest side of Mono Craters, the chemical composition of the rocks in the Mono Craters does not appear to have changed during the course of their eruption.

It has been suggested that three magma chambers underlie the subject area (figure 1): (1) beneath the proposed ring fracture system in the June Lake area along whose eastern margin occur the Mono Craters, (2) beneath Mono Lake and (3) beneath the Long Valley Caldera (Bailey et al., 1976). Most of the rocks erupted in the Mono Craters are chemically homogeneous rhyolite (Carmichael, 1967; Jack and Carmichael, 1968), and are thought to have come from a magma chamber beneath the Mono Craters. However, because the rocks in the Inyo Craters are a heterogeneous mixture of two compositions--rhyolite and rhyodacite--it has

en suggested (Bailey et al., 1976) that the rocks at these eruptive centers represent mixing of rhyolite magma from the chamber beneath Mono Craters with rhyodacite magma from the chamber beneath Inyo Craters and rhyodacite magma from the chamber beneath the Long Valley Caldera.

Types of eruptions: Three types of erupted pyroclastic material characterize the explosive eruptions in the area. Plinian eruptions involving the flashing of steam in pre-existing rocks have excavated small (less than 0.3 km diameter) craters on the north side of Mammoth Mountain, the two Inyo Crater Lakes, two craters in the Glass Creek area, and other craters buried beneath a mantle of more recent pyroclastics. The ejecta from these explosions appear to be mostly mud blocks of pre-existing rock that are deposited locally about the rim of the craters. No primary ash or lava were ejected in these explosions. They may have been initiated by magma rising to shallow depths and flashing groundwater (Bailey et al., 1976) or alternatively, tectonic faulting may have released confining pressure on already superheated groundwater.

A second type of ejecta involves primary gray and white pumice and concuous lithic fragments of basement rocks. This ejecta occurs as tephra layers up to a meter thick. The eruptions responsible for these tephra clearly involved the explosive ejection of fresh magma, but are not so voluminous or widely dispersed as eruptions of a third kind that poured out large volumes of fresh white pumice and ash.

The third type of ejecta involves thick, massive accumulations (greater than 0.5m) of white pumice bombs and lapilli within several kilometers of the vent and regionally dispersed lobes of fallout pumice lapilli and ash that extend 100 or more kilometers from the vent. These tephra layers are the result of the Plinian type eruption. Plinian eruptions involve continuous release of gas and pumice that forms spectacular convection plumes that

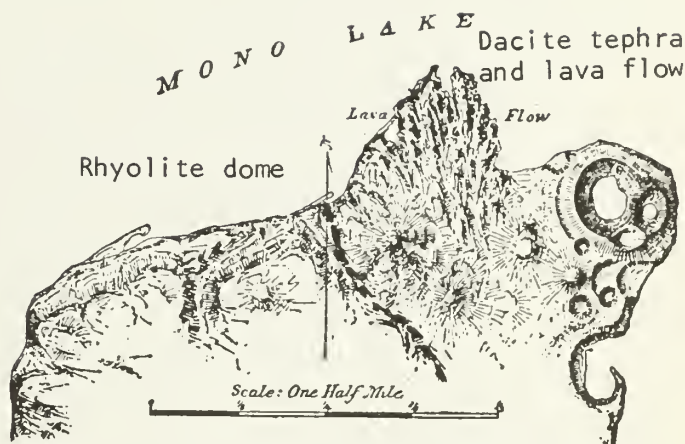


Figure 4. Geologic map of the north end of Paoha Island, after Russell (1889), with modifications from Lajoie (1968), showing multiplicity of volcanic events.

rise to heights exceeding 10 km and are blown long distances by atmospheric and stratospheric air currents resulting in widely dispersed and usually well sorted tephra layers. The May 18, 1980 and subsequent eruptions of Mount St. Helens have been of this type. Plinian eruptions also produce ash and pumice flows down the flanks of volcanoes or into valleys surrounding the vents. Two moderate-to-large size Plinian eruptions have occurred in the Mono-Inyo chain within the last 2000 years and produced widespread tephra documented by Wood (1977a). Other Plinian eruptions are also preserved within the late Quaternary deposits of the area, but none have been systematically studied.

A considerable new literature describes new techniques for evaluating the nature of pyroclastic deposits, much of which is referenced or summarized in publications by Fisher (1979), Sparks and others (1973), and Walker (1973). Hopefully future investigators will systematically evaluate the nature of the volcanic events recorded in the pyroclastic layers about the Mono and Inyo chain.

The final volcanic edifices of the Mono-Inyo chain and the Long Valley post-

caldera volcanoes are largely silicic domes and flows that are steep sided masses of rhyolite and obsidian (photo 1) Final emplacement of the dome or flow usually marks the end of an eruptive episode from a vent; however, appearance of the dome in the vent following an explosive pyroclastic eruption is not an indication of the end of the explosive eruptions. Many domes are blown away by both phreatic and magmatic explosive eruptions, and some large domes become gravitationally unstable and collapse as block and ash avalanches.

Mechanism of eruptions: It is important to examine the seismic record and the sequence of volcanic events that precedes and accompanies eruptions similar to those that have occurred in the Mono Basin-Long Valley area. Unfortunately, most of our detailed earthquake sequences are from silicic eruptions within the calc-alkaline belts of volcanic arcs associated with subduction zones and from basaltic eruptions on mid-ocean islands such as Hawaii. We do not have such detailed records of seismicity associated with volcanism in block-faulted structural provinces within continental plates, such as the Mono Basin-Long Valley area. Nevertheless, silicic magma eruptions may go through similar stages and associated seismicity regardless of tectonic setting, simply because of the similarity of the viscosity of the magma.

A sequence of stages of a new eruptive episode in the Mono Basin-Long Valley area might proceed as follows:

- Stage 1 - Earthquakes along the Sierra Nevada Frontal fault system which open fissures or lessen the horizontal confining pressure along faults reaching the magma chamber.
- Stage 2 - Viscous siliceous magma rises towards surface along these weakened fractures; at the same time groundwater may leak downward.

Stage 3 - When contact is made a steam explosion displaces pre-existing volcanic and lacustrine sediments forming a crater.

Stage 4 - If magma continues to rise eruptions continue, changing in character from phreatic (steam) to phreatomagmatic and eventually magmatic with the formation of a new dome.

If this sequence of events is the mechanism in the Long Valley area, it is possible that we are in stage 1, and nearing stage 2 with the ongoing seismicity that has followed the May, 1980 swarm. The mechanism requires large, fissure-producing tectonic quakes (apparently indistinguishable from A-type volcanic quakes of Minakami (1974) before the eruptive phase. This sequence of events is not new to volcanology and has been documented for several eruptions of Usu Japan (Minakami, 1974); Raoul Island, New Zealand (Adams and Dibble, 1967); Mauna Loa, U.S.A. (Macdonald, 1972) Mirapi, Indonesia (Shimozuru, *et al.*, 1969); Kloucheuskoi, U.S.S.R. (Gorshkov, 1960); and Vesuvius, Italy (Macdonald, 1972). The precursory earthquake pattern for eruptions apparently is more characteristic of viscous, high-silica lava rather than for basaltic lavas. The time lag between a major earthquake swarm and the actual eruption varies from 4 days to 6 months for the first 5 examples cited, that for the 79 A.D. Vesuvius eruption was 16 years (Macdonald, 1972). The time lag that could be expected for the highly viscous lavas of the Mono Basin Long Valley region would probably be on the order of 6 months to 10 years as a preliminary estimate.

The most recent eruption (described below) in the subject area was preceded by 11 months by a 5.7 magnitude earthquake near Mammoth Lake. Magnitude was estimated by Topozada *et al.*, (in press,

The region's most recent eruption deserves special discussion. Happenir

NORTH GLASS
CREEK DOME,
#32

SOUTH GLASS
CREEK DOME,
#34

LEE VINING

WILSON
BUTTE

PUNCHBOWL
DOME

SOUTH COULEE, #22

NEGIT ISLAND

PACHA ISLAND,
#1, 39

CRATER MOUNTAIN

MONO LAKE

U.S. 395

Photograph 1. Aerial view (to northwest) of Mono Craters and Mono Lake region, California. Numbers correlate with those used in figure 1 and table 2 (from CDMG photo files).

on the 23rd of August, 1890, this event was apparently witnessed by very few people in this then relatively desolate area. The Homer Mining Index of Lundy, Mono County reportedly contains an account of the event. No copies of the Homer Mining Index for late summer 1890 have been located. Townley and Maxwell's (1939) description from the Homer Index consists of:

"Remarkable earthquake at Mono.-- The southern end of Mono Lake was considerably agitated last Sunday, and dwellers in that shaky locality were much perturbed. Steam was issuing from the lake as far as could be seen, in sudden puffs, and the water was boiling fiercely, while high waves rolled upon the beach and receding left the sand smoking. In a moment the air was thick with blinding hot sulphurous vapor, and subterranean moans and rumblings made the witness think that the devil was holding high carnival down below. The fences wobbled up and down and sideways.

"This appalling fracas lasted about two minutes. Then came a blessed quiet for a moment, followed by a sudden twitch of the earth, as a horse jerks his hide and dislodges a bothersome fly. The shock threw men and animals off their feet with bruising violence.

"It was some hours before the lake ceased to emit columns of steam and the water became very hot. Two springs near the house long noted for the coldness and purity of their water, changed their character and spouted hot mud for two days, when they flowed cold water again. A stack of 200 tons of hay was moved 70 feet south without disarranging it."

There is little doubt that this event is not a classical tectonic earthquake. None of the newspapers in the surrounding communities of Bodie, Bishop, Bridgeport, Mariposa, California or Hawthorne, Nevada

report residents feeling an earthquake in August (Topozada et al., 1980 in press).

The local intensity pattern, event description, and location within a Holocene volcanic field lead us to conclude that the event was a sublacustral volcanic explosion. This evaluation is in agreement with the concluded volcanic origin for the event as contained in Chesterman (1971) and Christensen and Gilbert (1964). Minakami (1974) includes such events in one of his four categories of volcanic earthquakes. They are distinguished from tectonic earthquakes by showing an exceeding predominance of longer wavelengths, and according to Minakami (1974), are never felt more than a few kilometers from the source.

OBSIDIAN HYDRATION RIND DATING

Obsidian hydration rind dating is a method dependant upon a constant rate and recognizable mode of weathering found in natural and man-made silica glass. The method was originally developed for and applied to dating obsidian artifacts in archaeological studies in the 1960's. Because the method is rapid and inexpensive, a large volume of hydration rind measurements and independent age assessments have accumulated. This large volume of data has resulted in a solidly based confidence in the application of the dating technique and an awareness of its limitations (Packer, et al., 197

Because of the amorphous, homogenous character of glasses, the absorption of water (hydration) takes place at a uniform rate. In samples of the same composition and in the same physical surroundings, the rate of hydration is constant. Hydration rinds in obsidian are easily distinguishable in thin sections because the addition of water changes both the density and the volume of the hydrated layer. The change in density increases the index of refraction of the glass, and the change in volume causes mechanical strain throughout the layer, imparting the property of birefringence to the rim when viewed through

polarized light. Thus the hydrated rim (or rind) can be clearly detected and easily measured (within ± 0.3 microns) in thin sections studied under a polarizing microscope.

To be of optimum use as an age dating technique, the rate of hydration must be established for the particular environment and the particular obsidian chemistry from where the potentially datable samples are collected.

The hydration rate for a particular area and chemistry follows the diffusion equation:

$$M^2 = Kt$$

Where: M = the hydration rind thickness in microns

K = the diffusion constant in microns squared

t = time in years

It has been demonstrated by Friedman and Smith (1960) that diffusion constants are highly dependant upon temperature. Using age dates controlled by Carbon-14 and dendrochronology methods, they developed six worldwide diffusion constants: Arctic, sub-arctic, fast-temperate, slow-temperate, fast-tropical, and slow-tropical. The diffusion constants calculated range from 0.36 microns²/1000 years (for the Arctic), to 14.0 microns²/1000 years (for fast tropical). Friedman and Smith's (1960) fast- and slow-temperate diffusion constants came to 6.5 and 4.5 microns²/1000 years, respectively.

In spite of the wide range of values, these fall within single microclimates and have been derived from glassy samples of similar chemical composition have remained quite constant. As a relative dating technique on similar lavas from a single region, the method has few detractors. To apply Friedman and Smith's (1960) world diffusion constants to obtain ages in regions without local age control is not recommended.

Use of the age dating technique in the Mammoth-Inyo Craters region was accomplished

by Wood (1977a, 1977b). Because Friedman and Long (1976) have shown the considerable importance of temperature and rock chemistry in determining hydration rind rates, Wood (1977b) attempted to standardize these items for his samples. Obsidian domes and flows were sampled from north-facing, wholly or partly shaded outcrops, above ground and from elevations of from 2200 to 2700 meters. Petrologic and chemical data were obtained for representative sampling localities. This allows for recalculation of dates when locally age-controlled diffusion constants are revised. A tentative diffusion constant of 5 microns²/1000 years was used (Wood, 1977a, 1977b) to calculate preliminary dates as shown in Column 1 of table 2.

In compiling table 2 we have conservatively used a hydration rate of 5 microns²/1000 years to convert hydration rind thickness to age. The justification for using this rate is that this is the value of the rate needed to make the chronology of the pronounced change in magma type of the domes coincident with the same change of magma type found in radiocarbon dated, stratigraphic sequences of tephra reported in Wood (1977c). This is the well documented change in the Mono chain magma type from porphyritic to aphyric dated between 2000 and 3000 years (Wood, 1977b). Furthermore, this rate is reasonable for the climate in the area, and is the same rate originally assumed by Friedman (1968).

Wood and Brooks (1979) calculated a larger and more rapid hydration rate of 12.2 microns²/1000 years on the basis of Carbon-14 dating of a log buried by the most recent tephra from Panum Crater. This local age derived rate seems much too large and probably represents an upper limit. It is likely that this rate is high because it includes more rapid hydration that occurred at higher temperatures during the 5 to 50 years that it must have taken to cool the microenvironment of the dome. The still warm microenvironment of the Novarupta vent arising from the 1912 eruption of Mt. Katmai (Alaska) illustrates this point.

TABLE 2. COMPILATION OF AGE-DATED VOLCANIC EVENTS YOUNGER THAN 2000 YEARS IN THE LONG VALLEY - MONO BASIN OF EAST CENTRAL CALIFORNIA

CALENDAR DATE* OF ERUPTION	TYPE OF ERUPTION	SOURCE OF ERUPTION	DATING METHOD & LITERATURE SOURCE	ROCK TYPE
A.O. 1890	Sublacustral	Beneath Mono Lake, listed as #38, but location is conjectural	Historically documented observations (Tomley and Maxwell, 1939)	unknown
A.O. 1240 - 1855	Rhyodacite flows	Negit Island in Mono Lake	Stratigraphy of tephra on island (Wood, 1977b), and observations of Russell (1889), and Lajoie (1968)	rhyodacite
A.O. 1240 - 1855	dacite flows	#39 dome Paoha Island in Mono Lake		dacite
A.D. 1480 $\pm$ 200	Rhyolite dome extrusion	#5, cratered dome of Smith (1973), Mono Craters	Obsidian hydration (Wood, 1977b)	aphyric rhyolite
A.D. 1400 $\pm$ 60	Phraeatic explosion pit	#37, southernmost Inyo Crater, Long Valley	Carbon-14 (Wood, 1977a)	older rock and mud debris
A.O. 1400 $\pm$ 150	Phraeatic explosion pit	North side of Mammoth Mountain, Long Valley	Carbon-14 (R. Koeppen, & M. Rubin, U.S. Geol. Survey, personal communication, 1980)	older rock and mud debris
A.O. 1240 $\pm$ 60	Small-to-moderate-volume Plinian eruption, ash flow	#36 dome and tephra ring just south of Oadman Creek, one of the Inyo domes of Long Valley	Carbon-14, tephra 1 of Wood (1977a)	porphyritic pumice
A.O. 1240 $\pm$ 40	Small-volume Plinian eruption, and associated base surge, and block avalanche	#4, Panum Crater and dome, Mono Craters	Carbon-14 (Wood and Brooks, 1979)	aphyric pumice and obsidian
A.O. 1150 $\pm$ 200	Sublacustral doming, extrusion of obsidian	#1 dome on Paoha Island in Mono Lake	Obsidian hydration (Wood, 1977b)	obsidian
A.O. 1000 $\pm$	explosive eruption of tephra followed by dome	#7 dome on N. W. edge of Northwest Coulee, Mono Craters	Obsidian hydration (Wood, 1977b)	aphyric rhyolite
A.O. 980 $\pm$ 250	explosive eruptions of lithic debris and fresh pumice; Ten airfall layers and obsidian dome.	#32 & #34, Glass Creek domes of the Inyo domes, Long Valley	Carbon-14 (Wood, 1977b; R. Koeppen, R.A. Bailey and M. Rubin, U.S. Geol. Survey, personal communication, 1977)	porphyritic pumice and obsidian
A.O. 760 $\pm$ 80	Moderate-to-large Plinian eruption and emplacement of dome	#4, pumice pit just north of Panum Crater, Mono Craters	Carbon-14 (Wood, 1977b; Wood and Brooks, 1979), tephra 2 of Wood, 1977a)	aphyric pumice and obsidian
A.O. 500 $\pm$ 300	rhyolite and obsidian flow probably preceded by explosive tephra eruption	#8, N.W. part of the Northwest Coulee, Mono Craters	Obsidian hydration (Wood, 1977b)	aphyric rhyolite and obsidian
A.O. 280 $\pm$ 200	explosive eruption of pumice tephra	Tephra east and west of Mono Craters, source vent not known, Mono Craters	Carbon-14 (Wood, 1977b; and R. Bucknam, U.S. Geol. Survey, written communication, 1976)	aphyric pumice
A.O. 75 $\pm$ 300	obsidian flow	#9, Northwest Coulee, Mono Craters	Obsidian hydration (Wood, 1977b)	aphyric obsidian and rhyolite
0 $\pm$ 200	moderate-volume tephra eruption followed and obsidian flow	Tephra east of Mono Craters, probably associated with eruption of South Coulee, Mono Craters	Carbon-14 (Wood, 1977b) and obsidian hydration (Friedman, 1968)	aphyric pumice, obsidian & rhyolite
B.C. 300 $\pm$ 400	obsidian flow accompanied by tephra eruptions	#13 North Coulee, Mono Craters	Obsidian hydration (Wood, 1977b, and Friedman, 1968)	aphyric obsidian & rhyolite
B.C. 500 $\pm$ 400	explosive eruptions of tephra followed by dome	Wilson Butte, between Mono Craters and Inyo domes	Obsidian hydration (Wood, 1977b)	rhyolite & obsidian
B.C. 700 $\pm$ 800	dome extrusion	#21, Small dome in Mono Craters	Obsidian hydration (Wood, 1977b)	rhyolite & obsidian

* Carbon-14 ages have been corrected to calendar ages using the curve of Suess (1970). Hydration rind ages are calculated using a hydration rate of 5 microns²/1000 yrs. Plus-or-minus uncertainty associated with hydration rind ages are about one standard deviation of the histogram of rind thicknesses measured on samples from the same flow or dome.

FUTURE ERUPTIONS

Statistical probability

The recurrence of past eruptions is important in predicting the future volcanic activity of the area on a purely statistical basis. A histogram of the number of dated eruptions distributed in time is shown in figure 5. Readers are cautioned to keep in mind the limitations of the data. It is not always possible to associate distant and proximal radiocarbon dated tephra with any one of the hydration and dated domes. Because of this impression, one eruptive episode of pyroclastic eruptions that were terminated by a flow or dome, may appear as two separate eruptions on the histogram. On the other hand, many pyroclastic eruptions and possibly some domes have been missed due to complete burial by more recent tephra units. The average frequency of eruptions inferred from the data of figure 5 is about one per century.

Geologic Interpretation

Because of the physical, chemical, and textural differences of the eruptive products it is possible to distinguish what may be three somewhat independent potentially active volcanic systems (Lajoie, 1968, and Wood, 1977b). They are:

1. The Mono Lake group of rhyolite, rhyodacite lavas and lapilli tephra and the site of the reported 1890 eruption.
2. The Mono domes and craters group of aphyric rhyolite and obsidian.
3. The Inyo craters and domes of porphyritic rhyolite and obsidian (tentatively included in this group is the 15th century Mammoth Mtn phreatic eruption).

Based on the chronology of eruptions from different magma sequences and the inferred mechanism of eruption, the most likely loci of future volcanic events would appear to be at, or adjacent to the

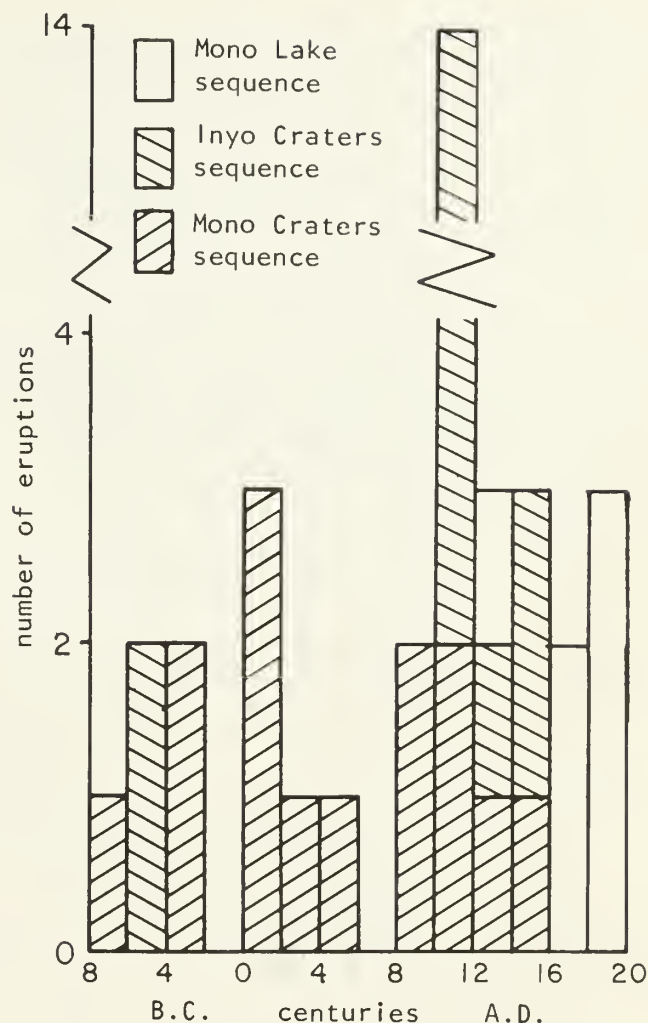


Figure 5. Histogram of number of eruptions per 200 years using obsidian rind hydration dates derived from Wood (1977b) and radiocarbon dates from sources listed in table 2.

most recent eruptive vents for each of the three volcanic systems. Described in terms of geographic landmarks, these regions would include areas within about 1.5 km. of Mammoth Mtn., Inyo Crater Lakes, Panum Crater, and Paoha Island.

CONCLUSIONS

All eruptions in the subject area during the past 2000 years have involved silicic magma, and have undoubtedly been accompanied by phreatic eruptions of lithic debris. All eruptive episodes have involved violent explosive activity. The data suggests that eruptions have

occurred on the average of one per century. There is little reason to believe that this pattern is going to change. Future eruptions will begin with an explosive phase. Hopefully, the initial eruptions will be heralded by a recognizable earthquake sequence and minor phreatic eruptions. Additional studies of past eruptions and careful analysis of the products will help establish the temporal behavior of an eruption episode, and the length and nature of eruptive recurrence intervals. What is lacking in our understanding of this scenario, and needed in order to develop a prediction potential is the earthquake pattern.

Perhaps the May, 1980 earthquakes in this area are a warning of events to come, and with this thought in mind, careful monitoring of seismic activity should continue for an indefinite period of time.

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VERTICAL CRUSTAL MOVEMENT FROM 1932 AND 1957 GEODETIC SURVEYS IN THE MAMMOTH LAKES - LONG VALLEY AREA, MONO COUNTY, CALIFORNIA

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The Mammoth Lakes earthquakes of May 1980 resulted in significant surface fracturing, notably along the Hilton Creek fault and numerous distributive faults north and northwesterly along its projection within the Long Valley caldera (Plate 1, Taylor and Bryant, this volume). Crustal movements resulting from seismic activity of the magnitude of the Mammoth Lakes earthquakes can be defined by re-survey of segments of any existing geodetic control networks that are within the area of crustal disturbance. In the Mammoth Lakes-Long Valley area, existing geodetic control suitable for this purpose consists of (a) a segment of a recently established U.S. Geological Survey trilateration (strain) network with a few lines of 20-30 km length spanning the epicentral area and (b) a National Geodetic Survey (NGS) first-order level line located along U.S. Highway 395. As of August 1980, no post-earthquake measurements have, as yet, been undertaken. The results of two earlier surveys of the NGS level line (1932 and 1957) are available, however, providing a measure of the relative vertical crustal integrity that existed within this region during this earlier 25-year period.

Prior to the 1980 earthquake sequence, the most significant seismic activity in the Mammoth Lakes-Long Valley area during this century occurred on September 14, 1941, during the period between the 1932 and 1957 surveys (Real *et al.*, 1978). The two largest events in this series had a magnitude (M) of approximately M 6. The only other earthquake of $M > 5.5$ to occur in this region during this 25-year period was a M 5.7 event in 1938. The composite epicenter for the 1941 earthquake sequence has been located near Toms Place and the

Hilton Creek fault (Figure 1) in close proximity to the larger events of the recent earthquake series. Cramer and Topozada (this volume) conclude, however, that the principal events of the May 1980 sequence are located west of the Hilton Creek fault and, therefore, are not consistent with a failure along this presumably east-dipping normal fault. It is uncertain, therefore, whether the 1980 earthquakes represent renewed activity of the same feature(s) that were active during the 1941 sequence.

Results of the 1932 and 1957 leveling surveys are compared in Figure 1. Also shown are bench mark locations, topographic profile along the level route and epicentral locations of the three largest ($M \geq 6$) earthquakes of the May 1980 series. The comparative survey data compiled in Figure 1 extends southeasterly across the caldera from the northern rim near Crestview to the southern rim near its juncture with the Hilton Creek fault, and beyond to Sherwin Summit, a total distance of approximately 47 km. For this comparison, elevation differences are computed relative to bench mark "7723" near Crestview, assumed invariant in elevation. The comparative data are based on observed field elevations.

Both the 1932 and 1957 surveys were conducted by the National Geodetic Survey to first-order (Class II) specifications. Leveling precision is estimated using the relationship $\sigma = bD$ where σ = the standard deviation of the elevation difference determined from leveling over the distance "D" in kilometers; "b" is conservatively assumed to be 1.0 mm. The standard deviation of the difference between two leveling surveys is equal to the square

root of the sum of the squares of the standard deviations of the individual levelings; over the 47 km route considered in this comparison, one standard deviation equals about 10 mm.

Referring to the comparative survey data in Figure 1, the five bench marks located northerly of Casa Diablo to and across the northern caldera boundary near Crestview exhibit relative stability, with only small random differential changes between the two surveys (documented surface rupture resulting from the May 1980 earthquakes was also lacking northerly of Casa Diablo). Similarly, at the southeasterly end of this comparative profile, the four bench marks southerly of Toms Place exhibit a corresponding virtual absence of any relative differential change between the two surveys. Between these locations of relative stability, the indicated elevation change over the entire route is 20-25 mm, or about two standard deviations, and, therefore, of marginal significance. This net difference does not develop uniformly, however, and, in fact, the comparative data reflects definite points of inflection or differential changes that suggest actual movement, albeit of small magnitude. Relative movement is indicated, for example, in the immediate vicinity of Casa Diablo, as evidenced by a 20 mm+ change between bench marks "7581" and "Z123". Cramer and Topozada (this volume) determined from microearthquake studies that near-continuous seismic activity that occurred for 9 months prior to the May 1980, earthquake series was predominant in the immediate area of Casa Diablo. Initial and gradual failure eventually leading to the 1980 earthquake sequence appears to have occurred in this area and, possibly, the small elevation changes noted here reflect some earlier modest structural adjustment of the same feature(s).

Again referring to Figure 1, bench mark "7066", located in a volcanic outcrop near the Hilton Creek fault just north of Highway 395, indicates no elevation change relative to the previously noted "stable"

bench marks south of Toms Place. Southeast of this mark, however, across the Hilton Creek fault and southern rim of the caldera, the next several marks located along the westerly margin of Lake Crowley reflect progressive changes that suggest a slight tilting of the block easterly of the fault. This series of bench marks are located in large moraine boulders, a bridge, and outcrops of granite. Thus, the consistent changes are not attributable to gradual settlement of bench marks located in unconsolidated deposits which are common through this area. These very small differences could be related to the initial loading of adjacent Lake Crowley during 1941, ascribed to minor crustal adjustment as a consequence of the 1941 earthquakes. The abrupt termination of this relative downward trend in the immediate vicinity of Toms Place (as evidenced by the 15 mm difference between bench marks F124 and G124) is suggestive of a possible structural discontinuity in this vicinity.

CONCLUSIONS

The differences between the two surveys are minor, indicating relative vertical crustal stability in this region between 1932 and 1957. Small differential changes indicated near Casa Diablo and Lake Crowley are probably indicative of very minor regional crustal adjustments resulting from the 1941 earthquake sequence. Notably, if the 1941 earthquake activity was the result of failure on the Hilton Creek fault (as implied by its epicentral location), then this activity produced no more than a few millimeters of vertical fault movement at the surface. Alternatively, if both the 1941 and 1980 earthquakes are of similar origin, involving more complex and relatively distributed adjustments along and southerly of the caldera boundary, geodetic evidence of vertical crustal movement resulting from the 1980 activity may be lacking, as it is for the 1941 sequence. In that event, the numerous surface fractures that result from the recent earthquakes would be attributable to secondary failures resulting from earthquake shaking.

Numerous supplementary bench marks were added during the 1957 survey of this line. Hopefully, a resurvey will be made in the near future which will permit substantive conclusions concerning vertical movements associated with the 1980 earthquake series.

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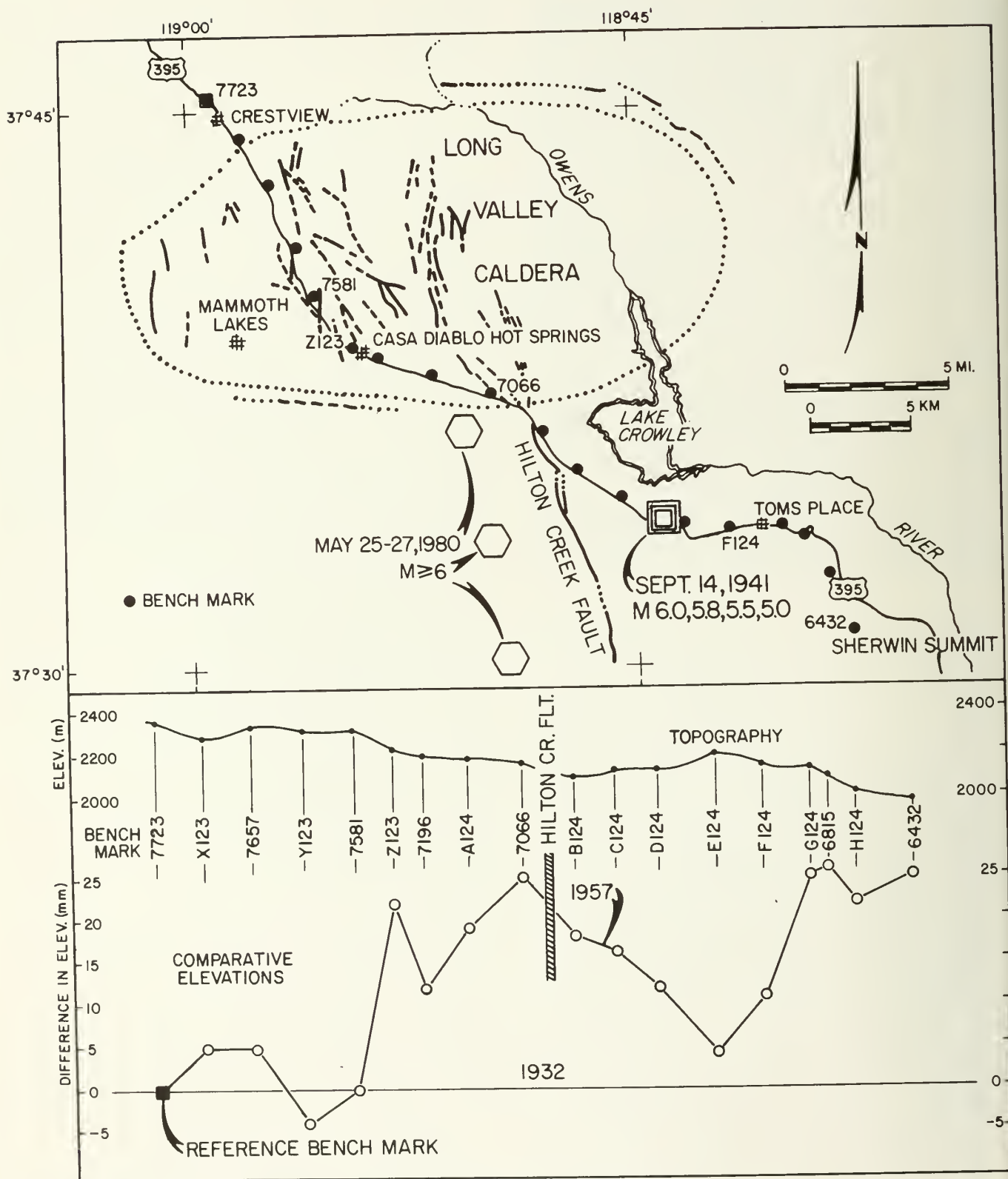


Figure 1. Location of bench marks, topographic profile and comparative elevation derived from 1932 and 1957 geodetic leveling surveys across Long Valley caldera. Epicenters of the 1941 earthquakes and major $M \geq 6$ events of the 1980 series are included.

SPATIAL-TEMPORAL VARIATIONS IN SEISMICITY PRECEDING
THE MAY, 1980, MAMMOTH LAKES, CALIFORNIA, EARTHQUAKES

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ABSTRACT

Anomalous temporal variations in the southern part of the Sierra Nevada-Great Basin boundary zone (SNGBZ) from 1977 to 1980 followed a pattern that several authors have identified as precursory to strong earthquakes. From October, 1977 to September, 1978 a general decrease in seismicity was observed in the southern part of the zone, followed by a burst of moderate earthquakes from Doyle in the northern part of the SNGBZ to Bishop in the south. The 1977-1979 variations are particularly noteworthy because they occurred over the entire SNGBZ, indicating a regional, rather than local cause. In the southern part of the zone, a magnitude 5.7 shock 25 km northwest of Bishop on October 4, 1978 was followed by an earthquake swarm in the Mammoth Lakes area, with peaks in activity during late 1979 and the spring of 1980. The Mammoth Lakes activity spread gradually to the west during the first year of this sequence, apparently involving several northerly-trending fracture zones in an area of about 900 km². Bursts of activity from December, 1979, to April, 1980 had increasingly dense spatial clustering. Temporal clustering showed monthly peaks in the spring of 1980, and intense swarming occurred in mid-May, about ten days before the largest events in the sequence.

The similarity between this sequence and seismicity patterns observed before large earthquakes in other parts of the California-Nevada region was reported by the authors in public addresses and professional meetings from July, 1979 to April, 1980.

A search for changes in P-wave velocity changes within the SNGBZ, based on recordings of Nevada Test Site explosions

at pairs of stations, has so far produced negative results.

INTRODUCTION

Previous Observations of Precursory Seismicity

Attempts to define character of seismicity preceding major earthquakes are now converging on anomalous patterns of earthquake occurrence, either within the impending rupture zone or in the immediate vicinity of the impending mainshock; however, published results are not entirely consistent from region to region. Early work on this problem was by Fedotov (1968, 1969), who found an increase in background seismicity about 15 years before most, but not all, large shocks in the Kurile-Kamchatka region. Nersesov *et al.* (1974) found a tendency for moderate shocks in the Garm region of Central Asia to be located in areas of relative quiescence but to occur at a time when activity in the region surrounding the focal zone was at a limiting high value. Kelleher and Savino (1975) concluded that major earthquakes around the northern and eastern Pacific were generally preceded by several decades of quiescence in the main rupture zone, although increased seismicity might occur in the vicinity of the impending mainshock. Jones and Molnar (1978) found foreshock activity preceding a large fraction of the world's major earthquakes, with a suggestion that seismicity in the vicinity of the impending mainshock increases to about twice the previous level three months before a large event. According to Keilis-Borok *et al.* (1978), anomalous clustering of earthquakes in time and space is a characteristic pattern of seismicity that precedes strong earthquakes.

In the western United States, Tocher (1958) concluded that large earthquakes in central California in 1868 and 1906 were preceded by a regional increase in seismicity, and a later study suggested that seismicity before the 1906 San Francisco earthquake was within the main rupture zone (see Figure 8 in Ryall *et al.* (1966). Kanamori (1978) and Ishida and Kanamori (1980) reported that the 1952 Kern County and 1971 San Fernando, California earthquakes were preceded by a 1 1/2 - 2 year period of quiescence, followed by tight clustering of activity around the epicenter of the impending mainshock. To explain this, they proposed a model of progressive stress concentration toward the eventual hypocenter.

For the Nevada region Ryall (1977) observed that a moderate level of seismicity, including felt earthquakes, occurred over periods of at least several decades in or near the rupture zones of two major historic earthquakes (1915 Pleasant Valley and 1954 Dixie Valley - Fairview Peak).

Seismicity of the SNGBZ

The Sierra Nevada-Great Basin boundary zone (SNGBZ); Figure 1 consists of a left-stepping, en-echelon system of N-S faults between the Garlock fault zone on the south and the Honey Lake depression at the northern end of the range. Seismic activity along this zone is related primarily to differential vertical separations between the Sierra Nevada (0.12 mm/year uplift) and the lower Great Basin region (0.01 mm/year uplift); fault separations across the zone vary from about 1.2 to 5.5 km. Individual boundary fault segments generally have length of 60-200 km, and have prehistoric to historic maximum displacements of up to 6-7 m (Slemmons *et al.*, 1979).

In general, the area shown on Figure 1 is structurally and seismically complex, and seismogenic processes within it can be associated with both faulting and volcanism (VanWormer and Ryall, 1980). Rupture times for specific fault segments

within the SNGBZ are long, of the order of several thousand years (Ryall, 1977; Wallace, 1977, 1978; Bell and Pease, 1980). Estimates of maximum magnitudes for this zone, based on a comparison of mapped faults with seismicity, range from 8.0 or greater in the area south of Bishop to 7.5-7.8 in the area between Bishop and Susanville (Ryall and VanWormer, 1980).



Figure 1. Western Nevada and eastern California, showing the Sierra Nevada-Great Basin boundary zone, general faults (Wright, 1976), and epicenters of small earthquakes for 1 January 1970-24 May 1980. Dense cluster of events in the southeast part of the zone is the 1978-1980 Mammoth Lake sequence.

Seismicity for 1970-1978 in the southern part of the SNGBZ is shown on Figure 2, together with faults taken from geologic maps of California (Jennings, 1977) and Nevada (Stewart and Carlson, 1978). In the lower right corner of the figure, dense clusters of faults at the northern end of the narrow Owens Valley zone spread out along the White Mountains block to the north and the Sierra Nevada frontal fault zone to the northwest. Seismicity in the area reflects this pattern, with epicentral lineups along NNE-trending groups of faults in the area just north of the 1872 Owens Valley rupture zone, and a dense cluster of epicenters extending toward Long Valley to the northwest. An earthquake with magnitude 5.7 on October 4, 1978 was located in the middle of this cluster. Little seismicity is observed between this group of epicenters and the prominent east-trending cluster in the area east of Mono Lake. This area of relatively low seismicity includes the Long Valley Caldera, where Steeples and Pitt (1976) reported that a month-long survey of microearthquakes in 1973 revealed very little activity within the caldera.

In the region north of Owens Valley, interpretive maps by various authors (Stewart, 1979; Wright, 1976; Gilbert and Reynolds, 1973) show fault segments 30-70 km long, corresponding to maximum magnitudes of 6.6-7.5 (Ryall and VanWormer, 1980). If an earthquake involved rupturing along the entire 120 km-long fault group from Bishop to Bridgeport, it could have magnitude of 8.0.

SPATIAL-TEMPORAL VARIATIONS

Regional Variations

The spatial-temporal character of seismicity in the SNGBZ is illustrated by Figure 3, which shows earthquake occurrence as a function of time and latitude, for events recorded by the dense Mina and Reno seismic networks for 1 June 1970-30 April 1980. The figure also shows a running b-value (slope of the recurrence curve, $\log N = a - bM$), determined for

overlapping groups of 200 events each. The b-values were determined by a maximum likelihood calculation (Aki, 1965) using only SNGBZ events south of latitude 39°N and with magnitude $M > 2.3$.

As noted by VanWormer and Ryall (1980), uneven network coverage for the period shown on the figure has affected the detection and analysis of events with $M < 3.0$ in some areas. This is reflected on the figure (i.e., "gap" in late 1975 and early 1976 at Reno, due to lack of data); however, fluctuations in network detection capability have been taken into account in the discussion that follows.

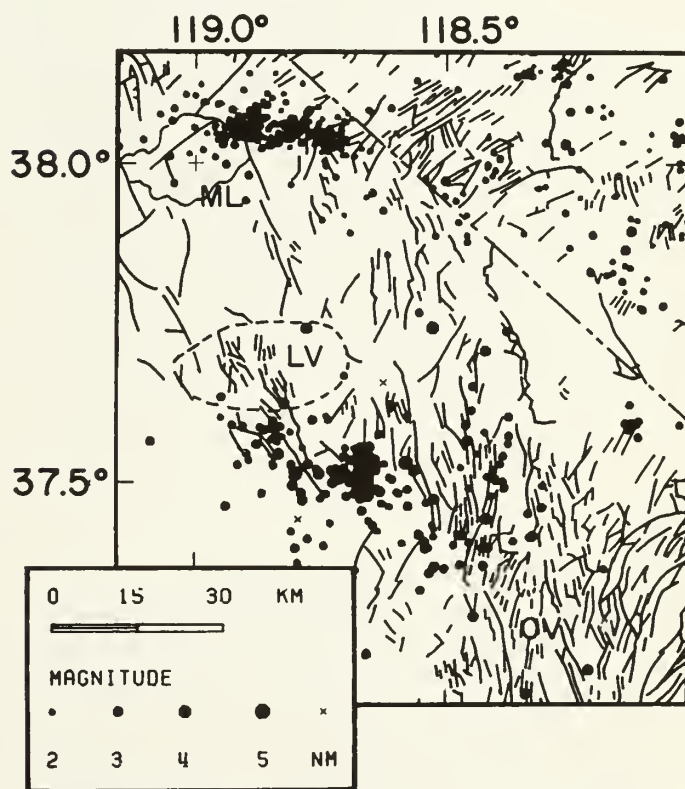


Figure 2. Southern part of the SNGBZ, showing mapped faults (Jennings, 1977; Stewart and Carlson, 1978). Dots -- earthquakes recorded by University of Nevada seismic network for the period 1970-1978. ML -- Mono Lake; LV -- Long Valley; OV -- north end of the Owens Valley. Outline of Long Valley caldera shown by dashed line.

Table 1. SGNBZ earthquakes with $M_L \geq 4.5$, 1975 to May 25, 1980.

Date			Time	Lat.	Long.	M_L	Description
Yr	Mo	Day	GMT	Deg N	Deg W		
1975	12	10	1919	37.499	118.418	4.5	North of Bishop
1976	6	20	1015	40.407	120.350	4.5	Near Susanville
1976	7	7	1827	37.433	118.550	4.6	Northwest of Bishop
1977	2	22	0624	38.488	119.285	4.9	Near Bridgeport
1978	9	4	0452	38.796	119.795	4.6	Near Markleeville
1978	9	4	2154	38.794	119.790	5.2	Near Markleeville
1978	10	4	1642	37.493	118.673	5.7	Northwest of Bishop
1978	10	4	1739	37.592	118.650	4.9	Bishop aftershock
1978	10	5	0117	37.572	118.643	4.5	Bishop aftershock
1979	1	24	2114	37.561	118.576	4.5	Bishop aftershock
1979	2	22	1557	39.992	120.105	5.1	Doyle
1979	10	7	2054	38.233	119.352	4.9	Bridgeport
1980	5	25	1633	37.585	118.815	6.0	South of Mammoth Lakes

The most dramatic feature on the figure is a general decrease in activity in the southern part of the zone from the fall of 1977 to the fall of 1978, followed by a burst of sizeable earthquakes, aftershocks and swarms in all parts of the zone in late 1978 and 1979. Table 1, chronologically listing events with $M_L \geq 4.5$ in the zone for the period June, 1976 to June, 1979, illustrates this change in activity. Of the thirteen earthquakes in the table, seven occurred in a six-month period from September, 1978 to February, 1979, and these were distributed along 300 km of the SGNBZ, from Doyle in the north to Bishop in the south.

When the earthquake distribution on Figure 3 is examined in detail, there is a suggestion that the occurrence of a

sizeable event in one part of the Sierra boundary zone affects ongoing activity in other parts. Figure 4 shows the distribution of earthquakes in the zone for the period of increased seismicity, August 1978-December 31, 1979. In a number of cases, gaps in activity in the southern part of the zone correspond to the occurrence of large events in other areas. Thus an ongoing swarm at Mono Lake (latitude 38°N) in the fall of 1978 stopped during the period of mainshock-aftershock sequences at Markleeville (38.8°N) and Bishop (37.5°N), respectively in September and October, 1978; similarly, the Bishop-Mammoth Lakes activity has gaps at the times of occurrence of large events at Doyle (40°N) and Bridgeport (38.2°N) in February and October, 1979.

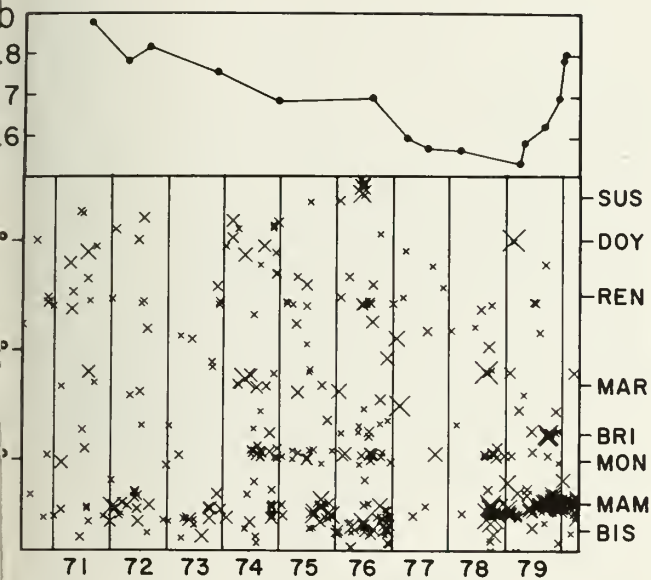


Figure 3. Earthquake occurrence in the SNGBZ as a function of time and latitude. Size of symbols is proportional to magnitude. Only events with $M > 2.3$ are shown. Location of zone is shown on Figure 1. Abbreviations on right side of figure show place names corresponding to the latitude scale on left, from top to bottom: Susanville, Doyle, Reno, Markleeville, Bridgeport, Mono Lake, Mammoth Lakes, Bishop. Top of figure shows a running b-value for events south of 39°N latitude, based on overlapping samples of 200 events each.

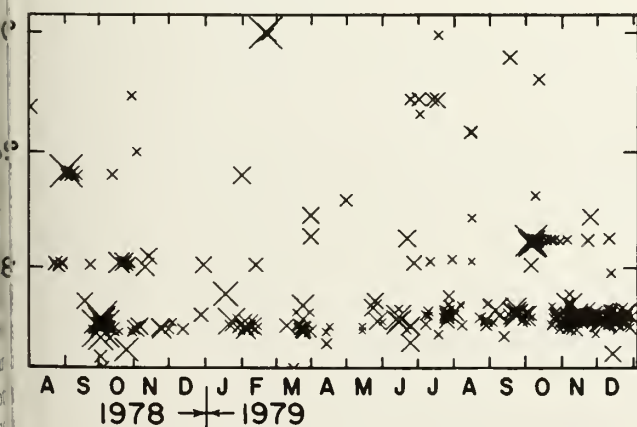


Figure 4. Same as Figure 3, but with time scale expanded to show additional detail for the 1978-1979 period.

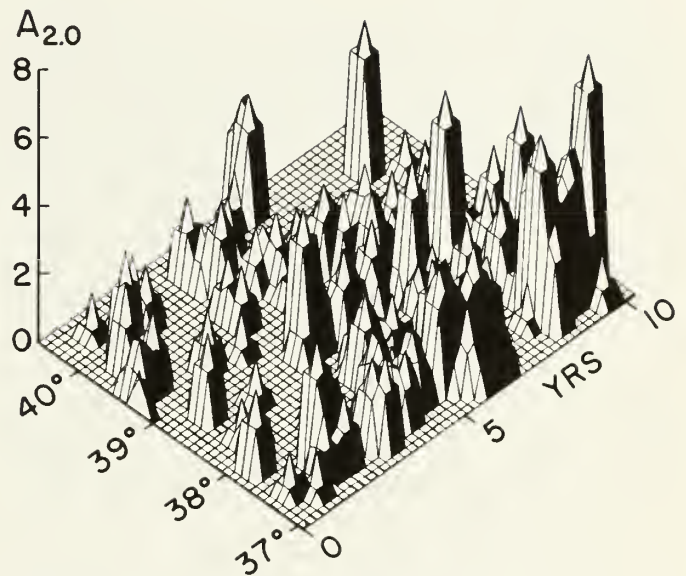


Figure 5. Energy released by earthquakes in the SNGBZ as a function of time and latitude, for the period June 1, 1970-May 31, 1980. $A(2.0)$ logarithm of the number of $M_L 2.0$ earthquakes that would be equivalent to the total energy released by earthquakes within a grid square ($10 \text{ km} \times 75 \text{ days}$). Numbers were smoothed with a triangular filter before $\log N(2.0)$ was calculated. Energy was determined from Richter's (1958) formula $\log E = 11.8 + 1.5 M$.

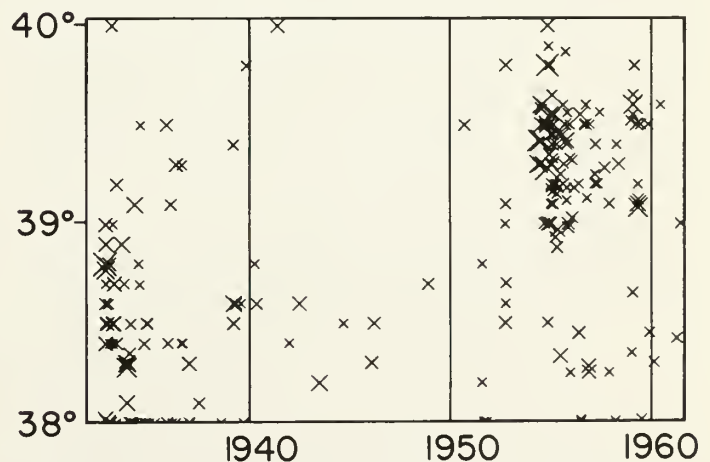


Figure 6. Distribution of earthquakes in central Nevada as a function of latitude and time. Plot includes events with latitude $38^\circ\text{--}40^\circ\text{N}$, longitude $117.5^\circ\text{--}119^\circ\text{W}$ and $M \geq 4$, from Slemmons *et al.* (1965).

The running b-value for the southern part of the SNGBZ, shown on top of Figure 3, indicates that the ratio of small-to-large earthquakes gradually decreased, from 0.815 to 0.533, over the period from 1970 to 1979, and during the last year of the sequence it increased rapidly to 0.800. Careful checking of magnitude calculations for the different periods of time, spot-checking of records to insure that large numbers of small events were not missed, and hand-plots of the data for selected periods of time all indicate that the change in recurrence rate was real and not an artifact of the analysis. This change will be discussed further in a later section.

Figure 5 is a three-dimensional plot showing earthquake energy release as a function of time and latitude within the SNGBZ. For the ten-year period shown, the level of activity in the entire zone is shown by this figure to gradually increase with time, with peaks in activity during late 1978 and 1979.

Comparison with Activity Preceding the 1954 Fairview Peak Earthquake

For comparison with Figure 3, Figure 6 shows a plot of earthquake activity in central Nevada (area bounded by latitude 38° - 40° N, longitude 117.5° - 119° W) as a function of time and latitude, for the period 1930-1962. The figure is based on locations and magnitudes listed in Slemmons *et al.* (1965), for earthquakes with $M \geq 4$. On the left side of the plot, activity during the first half of the 1930's represents mainshock/aftershock sequences at Cedar Mountain (1932, $M = 7.2$) and Excelsior Mountains (1934, $M = 6.3$). Seismicity in the Fairview Peak area is represented by a few events in the late 1930's; a twelve-year period of quiescence from 1940 to 1952; a group of 11 events in November, 1952 (largest $M = 4.8$) in the vicinity of the 1954 mainshock; a 19-month gap; and intense activity during the six-month period before the mainshock.

Spatially, the seismicity in the 1930's and 1940's was concentrated in the rupture

zones of the Cedar Mountain and Excelsior Mountains sequences, plus minor activity just east of the epicenter of the impending mainshock. In July and August, 1954 two earthquakes with magnitude 6.8 occurred at Rainbow Mountain and in the Stillwater area, respectively 16 and 19 km west and northwest of the mainshock, which occurred on December 16, 1954 and had magnitude 7.1. The latter was followed four minutes later by a magnitude 6.9 shock in Dixie Valley; aftershocks of these events have continued for more than 25 years and still constitute an area of high seismicity in the central Nevada region (Ryall, 1977).

Figure 7 shows a plot of energy release for the southern SNGBZ and the Dixie Valley-Fairview Peak area. Each plot is for a ten-year period, and only events with $M \geq 4$ were used in the compilation. Both plots show an increase in energy release with time, and in both cases the increased activity was distributed over sizeable region rather than concentrated in the vicinity of the impending mainshock. However, the burst of activity in July and August, 1954 released an order of magnitude more energy than the 1978 Bishop sequence and the swarm activity preceding the May, 1980 Mammoth Lakes events.

Local Variations

Distribution of the Bishop-Mammoth Lakes earthquakes in space and time is shown on Figures 8 and 9, respectively. These plots contain only events with "B" and "C" quality hypocenter solutions (Lahr and Lahr, 1975), and with depths in the range 3-10 km. Solutions with "D" quality, fixed depth, unusually small or large depth, and/or fixed latitude were rejected because of lack of network control. In these calculations, the HYP071 algorithm was used as a master event routine, by determining station time corrections appropriate to the Mammoth Lakes area. The four time periods shown on Figure 8 were selected on the basis of observed changes in the spatial distribution of seismicity, and vary from 38 to 432 days.

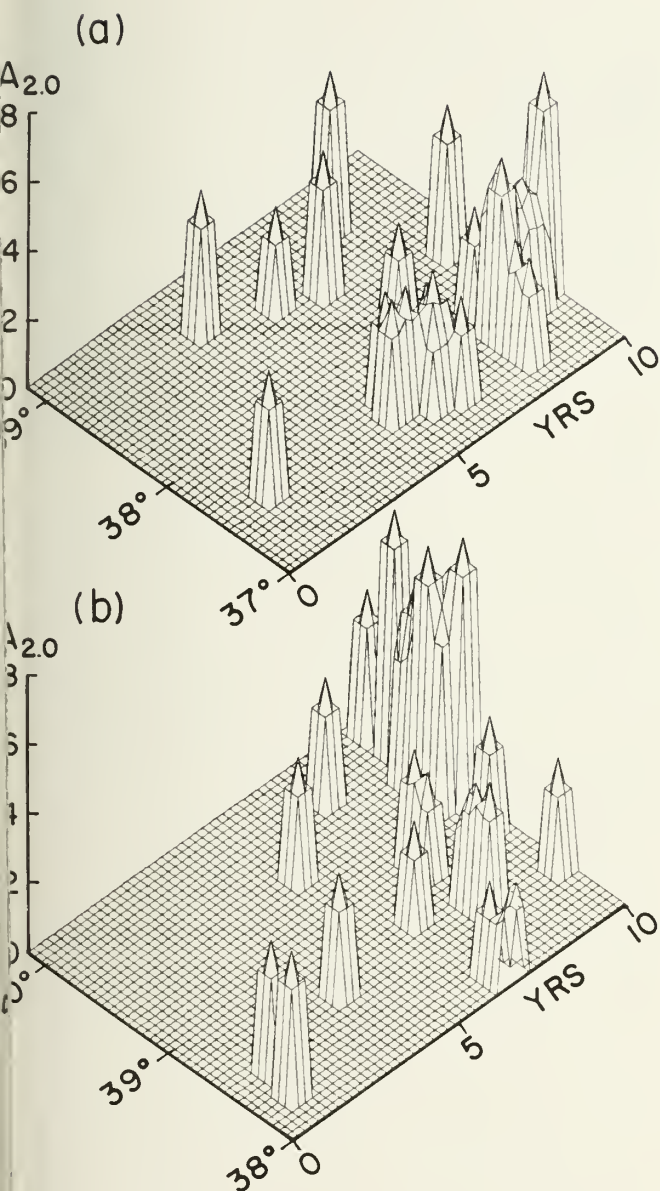


Figure 7. Energy release as a function of latitude and time, for (a) the southern SNGBZ and (b) central Nevada. Both plots include only events with $M \geq 4$; time periods were (a) June 1, 1970-May 31, 1980 and (b) January 1, 1945-December 31, 1954. Definition of $A(2.0)$ is the same as for Figure 5.

Figure 8a shows 61 events that occurred during the first 13 months of the sequence, from September 1, 1978, to November 6, 1979. The series started with the magnitude 5.7 event on October 4, 1978, and for about two months activity was

concentrated in the vicinity of the NNE-trending Wheeler Crest fault. In February and March, 1979, several events occurred in a N-S lineup south of the Hilton Creek fault. From April to early November, 1979, earthquakes were located in a 25-km long zone, trending NNE and extending under the Long Valley Caldera; during this same period a few earthquakes extended the original sequence to the southeast (lower right corner of Figure 8a).

From November 7 to December 18, 1979, the level of activity was high, and events were concentrated in an area south of the caldera and west of the Hilton Creek fault. Figure 8b shows 63 earthquakes for this period. From December 19, 1979 to April 17, 1980, 78 events on Figure 8c were located in three dense, NE-trending clusters west of the Hilton Creek fault. The remaining three earthquakes were on the southern part of that fault. During the last five weeks before May 25, Figure 8d shows 34 events in two dense clusters -- one at the caldera boundary and the other 5 km to the southeast, on the Hilton Creek fault. The ML 6.0 shock on May 25 was in the second of these clusters.

As the Bishop-Mammoth Lakes sequence progressed there were considerable fluctuations in the level of activity, and in the spring of 1980 the rate of occurrence increased and decreased on a monthly basis. Figure 9 shows a smoothed plot of the number of earthquakes per day for March, April and May, 1980. Peaks in activity can be seen in the latter parts of each month, with a very large peak about ten days before the large shocks on May 25. The largest number of events counted in a single day was 427 on May 16.

FOCAL MECHANISMS

Figure 10 shows P-wave first-motion plots for the large shocks on October 4, 1978 and May 25, 1980, plus one of the larger events of the Mammoth Lakes swarm on December 6, 1979. Teleseismic observations for Figure 10a were taken from the US Geological Survey's Earthquake Data Reports, and were provided by R. Needham

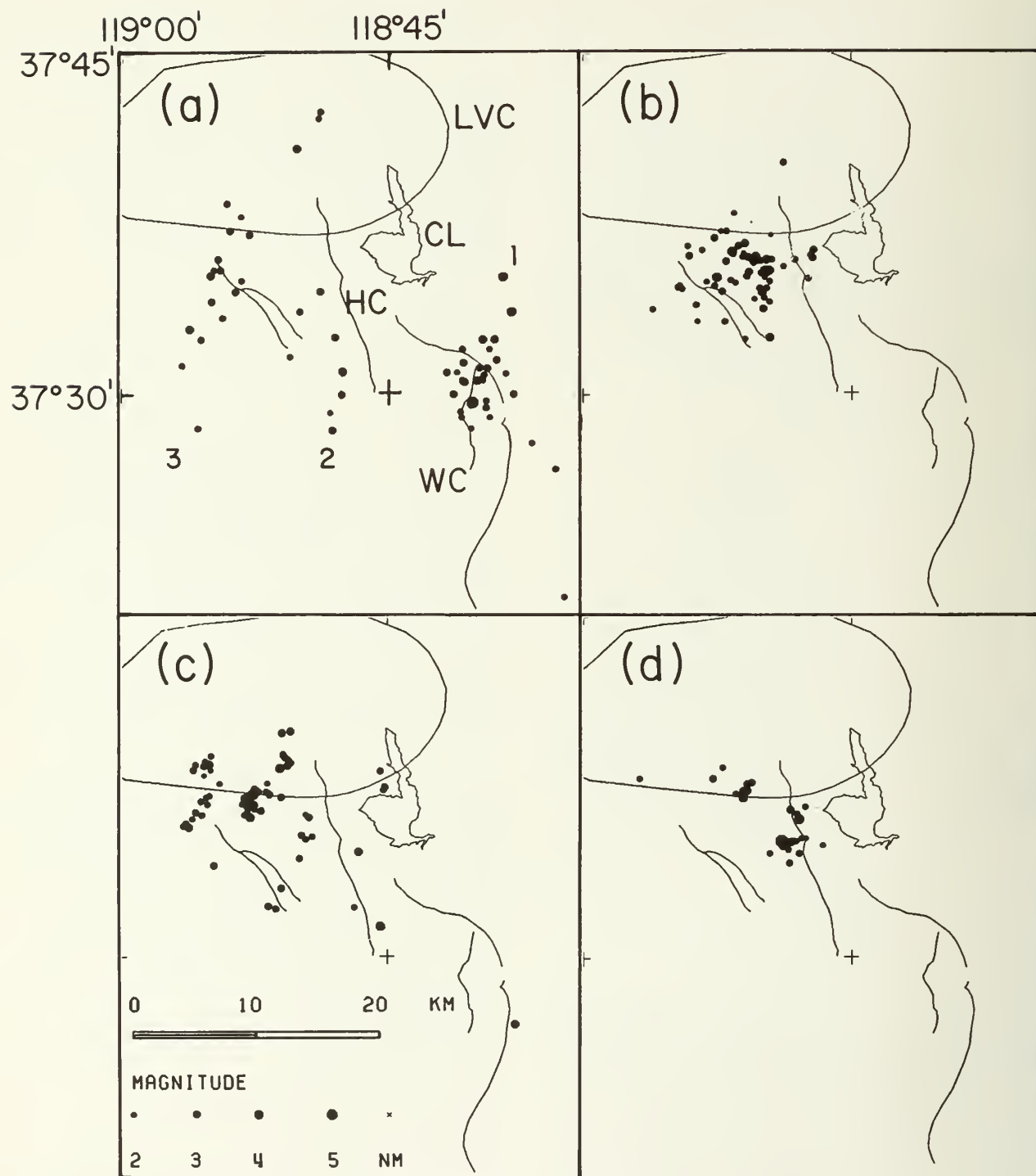


Figure 8. Epicenters of earthquakes in the Bishop-Mammoth Lakes area for 9/1/1978-5/25/1980, determined using the HYP071 algorithm (Lee and Lahr, 1975) with station corrections for this area. (a) -- 9/1/1978-11/6/1979; groups indicated by number are 1 -- 10/4-12/13/1978; 2 -- 2/7-3/26/1979; 3 -- 4/10-11/6/1979; (b) -- 11/7-12/18/1979; (c) -- 11/19/1979-4/17/1980; (d) -- 4/18-5/25/1980. LVC -- Long Valley Caldera; CL -- Crowley Lake; HC -- Hilton Creek fault; WC -- Wheeler Crest fault.

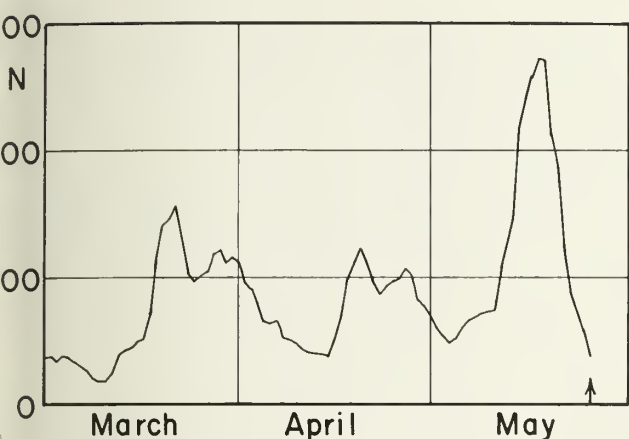


Figure 9. Number of events per day for March, April and May, 1980. Original counts from Helicorder records were smoothed by a five-day running average.

Figure 10c. While these figures show some arrivals that disagree with the interpretation, they all indicate one steeply-dipping plane striking NNE, in agreement with the earthquake lineups shown on Figure 8. Motion on these planes could be primarily left-lateral strike-slip. While this mechanism agrees with the strike of the Wheeler Crest fault (WC" on Figure 8a), it does not agree with other faults in the area south of the Caldera, which strike generally NNW. A discrepancy between the orientation of fracture zones at depth and that of surface features was noted previously for the SNGMZ by VanWormer and Ryall (1980), who noted that most moderate earthquakes in the zone from 1976 to 1979 had fault-plane solutions corresponding to right- or left-lateral slip on steeply dipping faults striking, respectively, NW or NE. They suggested that the discrepancy between such mechanisms and the N-S striking normal faults of the SNGMZ might be explained by block-faulting, with normal-oblique slip on the N-S striking faults and strike slip on NW- or NE-striking faults that terminate and offset the N-S segments.

SEARCH FOR VELOCITY CHANGES

To determine whether regional changes in seismic wave velocity might be associated with the observed regional changes in

seismicity, we analyzed P-wave arrival times for underground nuclear explosions at the Nevada Test Site. In this analysis, arrival-time differences were determined for pairs of stations that had almost identical azimuths (within a few degrees) to NTS, in order to eliminate effects due to differences in depth-of-burst and near-source structure. Stations that met this requirement are shown on Figure 11; shot-receiver distances were all greater than 180 km, so the phase measured was in all cases Pn. The original tape recordings were played out on strip-chart recordings at a time scale of 25 mm per second of real time, and arrival times measured from these records were accurate to within ± 0.02 second. The results of this analysis were negative: no systematic changes in velocity were detected, and the scatter was less than $\pm 1\%$.

DISCUSSION

The Bishop-Mammoth Lakes earthquake sequence displayed many of the characteristics that various authors have tentatively identified as precursory to large earthquakes. On a regional basis, the southern SNGMZ displayed abnormally low seismicity from October, 1977 to September, 1979, followed by intense activity in the Bishop-Mammoth Lakes area. This is similar to periods of quiescence observed by Kanamori (1980) before the 1952 Kern County and 1971 San Fernando earthquakes, and by us for the 1954 Rainbow Mountain-Stillwater-Dixie Valley-Fairview Peak sequence. The slow decrease followed by a rapid increase in b-value for the southern SNGMZ agrees with the pattern that Scholz *et al.* (1973) related to increasing effective differential stress, which they related in turn to dilatancy hardening. However, the duration of the "bay" -- about eight years -- would have been appropriate to an impending mainshock of magnitude 7 1/2, rather than 6.0. The spatial distribution of events -- initially dispersed over several crustal fracture zones and gradually concentrating in the vicinity of the impending mainshock -- is similar to patterns of cascading microshocks described by Scholz (1968) and Myachkin *et al.*

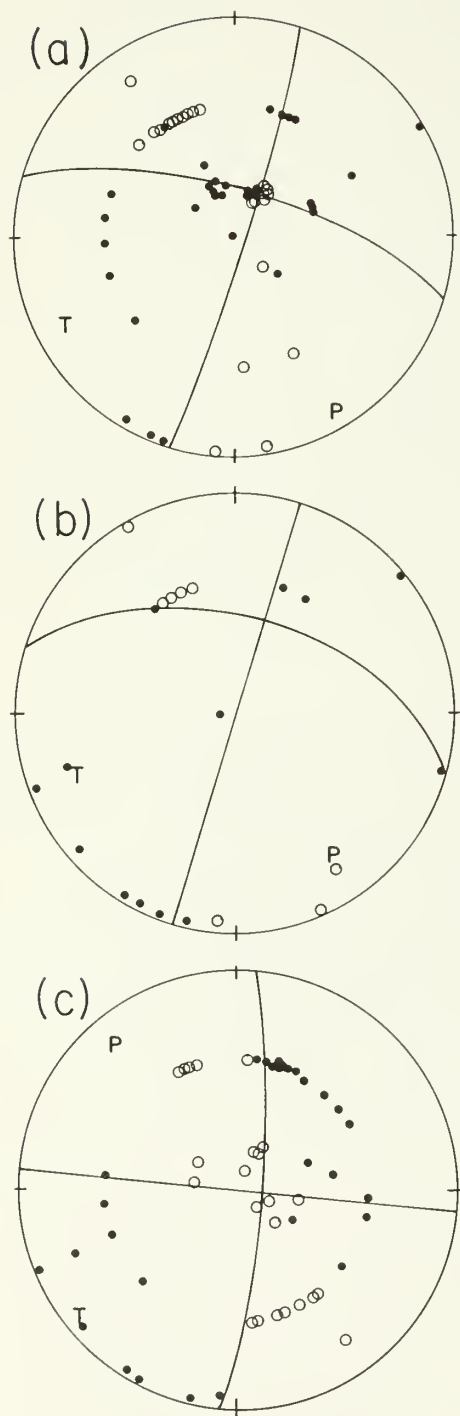


Figure 10. P-wave fault-plane solutions for selected events of the Bishop-Mammoth Lakes sequence. (a) -- M_L 5.7 event on October 4, 1978; (b) -- M_L 4.3 event on December 6, 1979; (c) M_L 6.0 event on May 25, 1980. Open circles -- dilatations; closed circles --

compressions; P, T axes of maximum and minimum compressive stress. Plots are lower-hemisphere, equal-area projections

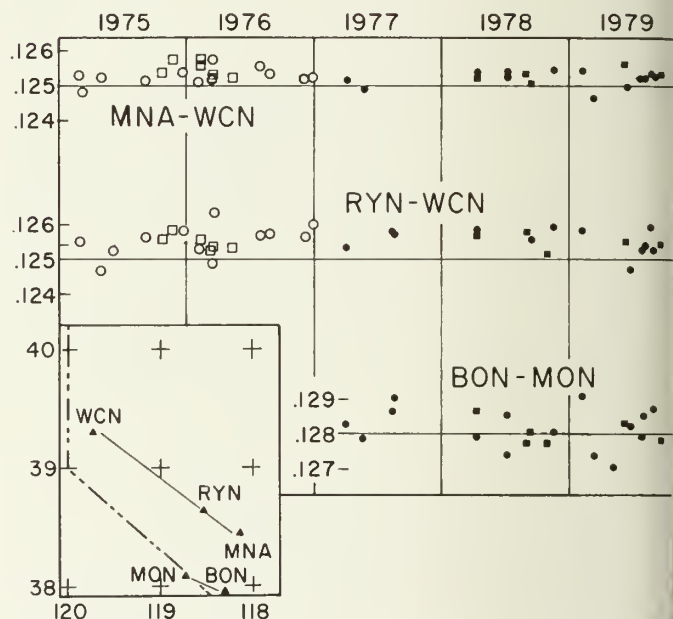


Figure 11. Plot of P_n slowness (sec/km) for Nevada Test Site explosions recorded at station pairs in the western Great Basin. Inset map shows station locations. Dots -- Yucca Valley shots; squares -- Pahute Mesa shots; open symbols -- data read from 10 mm/sec playbacks; closed symbols -- data read from 25 mm/sec playbacks.

1975) in laboratory fracturing experiments. This cascading effect was particularly dramatic toward the end of the precursory sequence, when the swarm activity reached a crescendo of 427 events on May 16, 1980, and then decreased to 43 events on the day before the first magnitude 6.0 shock. The area in which the sequence occurred -- approximately 30 x 30 km -- is anomalously large for Basin and Range swarms, in agreement with conditions stated by Aggarwal and Perez (1980) for recognizing precursory bursts of seismicity. The period of time, 599 days, between the beginning of the sequence on October 4, 1978 and the largest shocks on May 25, 1980, would have been appropriate for an earthquake of magnitude 6.6; the energy released by the three largest shocks on May 25 and 27 could be equivalent to a single earthquake of magnitude about 6.4. The sharp increase in energy release, and the occurrence of numerous moderate earthquakes along the SGBZ in late 1978 and 1979 agrees with characteristics of the "alarm periods" described by Keilis-Borok *et al.* (1978) for southern California earthquakes for the period 1932-1978.

The last observation suggests that the Shop-Mammoth Lakes sequence, as well as other precursory phenomena reported in the literature may have been the result of regional, rather than local stress changes. Also, such changes could create favorable conditions for large earthquakes to occur anywhere within a sizeable region, rather than in the immediate vicinity of the anomalous observation.

As this sequence continued, it became increasingly evident that we were dealing with precursory seismicity, and we presented a number of papers and public addresses concerning this probability. In July, 1979, we presented a paper (Ryall and Ryall, 1980a) that described the anomalous drop in seismicity and subsequent burst of moderate shocks along the SGBZ. We noted the similarity between this pattern and that observed by Kanamori (1978) for large southern California shocks. The same conclusion was restated in a paper submitted for publication in November,

1979 (VanWormer and Ryall, 1980). In late October, we installed three telemetering seismic stations and an accelerometer in the Crowley Lake area, to improve network hypocenter determinations and strong-motion coverage for the Mammoth Lakes swarm activity. On December 22, 1979, we presented a public lecture at Mammoth Lakes and described the evidence for an impending large earthquake. On January 23, 1980, we presented the same evidence to US Geological Survey administrators at a meeting in Menlo Park, California, and asked that the Mammoth Lakes area be designated a Special Study Zone. Finally, we presented a paper at the Annual Meeting of the Seismological Society of America on April 26, 1980 (Ryall and Ryall, 1980b; abstract submitted in January, 1980), in which we compared the SGBZ activity with precursory seismicity patterns observed elsewhere, and noted that the earthquake swarm around Crowley Lake was within a zone that had the potential for an earthquake of ML 7.5 or greater.

ACKNOWLEDGEMENTS

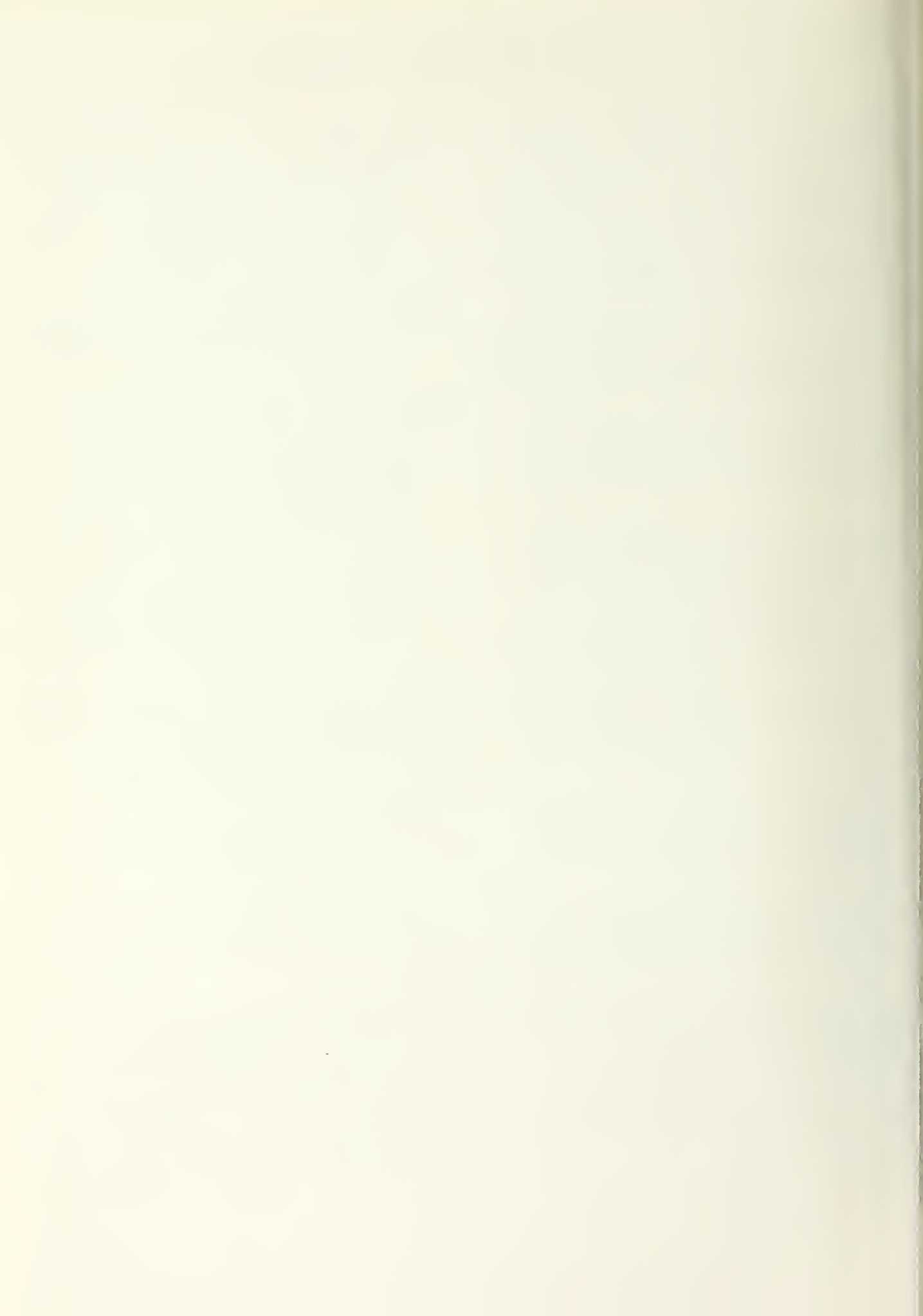
This research was partly supported by the US Geological Survey, under contract number 14-08-0001-16741. Much of the analysis of network data for the 1974-1978 period was either done or supervised by J. D. VanWormer before his death in July, 1979; he also noted the anomalous decrease of seismicity in 1977. Gloria Smith assisted with data analysis, and W. F. Nicks was responsible for operation of the Nevada network during the period covered by this study.

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A NOTE ON THE MAMMOTH LAKES, CALIFORNIA EARTHQUAKE CLEARINGHOUSE

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ABSTRACT

Selection of the earthquake clearinghouse site was aided by officials of local government and the site selected proved to be excellent. Additional staffing, telephone service, and reproduction equipment were needed for efficient operation. A similar sized earthquake in a more populated area may preclude the sharing of quarters with other service organizations.

INTRODUCTION

The clearinghouse activity is a part of the California Division of Mines and Geology (CDMG) response to a potentially destructive geologic hazard, which most often has been an earthquake. Following the onset of the Mammoth Lakes, California earthquake sequence of May, 1980, a clearinghouse was established at the Mammoth Lakes Firehouse. This report describes the goals of and the process of selecting an earthquake clearinghouse, the data collected at the clearinghouse, and suggests modifications for future operations.

CLEARINGHOUSE GOALS

The importance of a clearinghouse for making available information about earthquake recovery operations, hazards evaluation and investigations has been recognized (Stearns, 1972; Johnson, 1974), and reported upon (Sherburne, 1975). For the CDMG staff at a clearinghouse, the goals are (1) collection and dissemination of information, (2) directing CDMG field

investigations and (3) maintaining a liaison with local and state government and other scientific and engineering groups. The clearinghouse also represents a point of focus for scientists and engineers arriving in the area, for other members of the CDMG staff, other representatives of State Government (OES, CALTRANS, etc.), local government, concerned citizens, and the media.

The collection of information includes data related to post-earthquake field studies (for example, seismic monitoring and fault mapping) and hazard evaluation both of engineered structures and geologic environment. With several investigative groups having common goals, it is important that the duplication of effort be minimized whether it be related to instrument placement, damage assessment, or reports of geologic phenomenon. Relative to the last two items, observers are reminded that what was not seen at a location may be as important as what was seen, and frequently it becomes the role of clearinghouse staff to extract this information from observers. The information is collected in the form of comments collated with map references; this information is immediately available at the clearinghouse.

A prime post-earthquake responsibility of the Division of Mines and Geology is to conduct investigations related to geologic hazard evaluation; every effort possible must be made to reduce the risk associated with continuing or additional earthquake activity. Some obvious hazards in the Mammoth Lakes area which were examined were the Long Valley Dam, rock slides adjacent to developing or developed areas, locations of highway-fault crossings, and

locations of reported earthquake damage to engineered structures. Other basic scientific studies relate to geology, sensitive and strong motion ($>0.05g$) seismology; these studies improve the understanding of the earthquake potential of the region and permit a more enlightened program of land use planning.

THE MAMMOTH LAKES CLEARINGHOUSE

It is important that an earthquake clearinghouse be (a) centrally located, (b) easily identified, and (c) available for continuous operations. In addition, it must provide adequate communication service, a meeting room of a size adequate to facilitate evening clearinghouse sessions, and, of course, be capable of resisting damage from an earthquake.

At Mammoth Lakes, the problem of a suitable facility was resolved by discussing the needs with members of the Mono County Sheriff's Department substation staff, a representative of local government, and Fire Chief Jon Sweeney. The facilities at the Mammoth Lakes Firehouse were very good and the clearinghouse was operational by 10 a.m. on 26 May 1980; about 24 hours following the initial major shock. Operation of the clearinghouse was continued for $3\frac{1}{2}$ days. Meetings to exchange information were conducted Monday and Tuesday evenings, 26 and 27 May 1980. Information collected at the clearinghouse is shown in Table 1 and located on Figure 1. Instrument locations shown in that figure are tentative, and whether the instrument was installed should be verified by directly consulting the various investigators identified in the next section of this report. The collection and presentation of this preliminary information is very important because much of it represents first impressions of earthquake manifestations and may influence the planning of field studies and hazard evaluations.

SOURCES OF SEISMIC INSTRUMENTATION

The following is a list of organizations and lead scientists that are known to have had instruments operating either before or during this earthquake sequence.

John Anderson*	Scripps Institute of Oceanography U.C. San Diego La Jolla, CA 92093
Chris Cramer	CDMG 2815 "O" Street Sacramento, CA 958
Robert Fergeson	Seismographic Station U.C. Berkeley 475 Earth Sciences Bldg Berkeley, CA 94720
Carl Johnson	Seismological Laboratory California Institute of Technology Pasadena, CA 91125
Albert Lin	Civil Engineering California Institute of Technology Pasadena, CA 9112
Alan Ryall	Seismological Laboratory University of Nevada Reno, Nevada 8955
Paul Spudich	USGS 345 Middlefield Road Menlo Park, CA 940
Charles Turpin	CDMG-SMIP 2811 "O" Street Sacramento, CA 958

* At the time of this earthquake, Anderson was associated with University of Southern California, Los Angeles, CA.

FUTURE CLEARINGHOUSE OPERATIONS

For future clearinghouse operations, a larger staff is required to ensure a more complete collection of information and to provide a record of clearinghouse meetings. Clearinghouse staff and equipment should be promptly dispatched to the earthquake area with goals of locating the clearinghouse, collecting hazard information, establishing liaison with local government, and advising the media relative to what has happened and possible expectations. Portable reproduction equipment should be available; this equipment should be capable of reproducing significant portion of a standard 15' topographic map. Expanded telephone capability is generally needed and some type of advance statewide general agreement with the companies should be developed for increased short-term service.

Upon the occasion of a damaging earthquake, the location of the CDMG clearinghouse may be obtained by contacting either the appropriate CDMG district office or the CDMG headquarters in Sacramento; see Figure 2 for telephone numbers and district boundaries.

Although this clearinghouse functioned satisfactorily, it is realized that an earthquake of this size (M6-6½) and accompanying aftershocks in a more isolated and developed area would present problems not yet encountered and resultant difficulties not yet identified. It is conceivable that following a more destructive earthquake, that close cooperation of local service agencies; i.e. fire departments, with clearinghouse staff may not be possible.

ACKNOWLEDGEMENTS

The careful reading and giving of suggestions by John Bennett (CDMG) and Ron Alfors (CDMG) was appreciated. Their attention to detail made the preparation of this manuscript much easier.

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Table 1. Clearinghouse Sign-in and List of Observations

<u>DATE</u>	<u>OBSERVER</u>	<u>ORGANIZATION</u>	<u>MAP REFERENCE</u> (Figure 1)	<u>OBSERVATION/COMMENT</u>
26 May 1980	R. Relles	CIT		
	A. Lin	CIT		
	*	CDMG	1	Settlement cracks.
	*	CDMG	2	Settlement (cracks?), maybe faulting, landslide about noon.
	*	CDMG	3	Damage to school; reported as extensive, some structural.
	A. Gillespie	CIT	4	Probably secondary cracks in sand tongues crossing the Hilton Creek fault, but no evidence of offset south of McGee Creek right (southerly?) lateral moraine. Extensive avalanches
	J. Jones	CIT		
	A. Gillespie	CIT	5	Cracks along top of escarpment <1cm; some are just subsidence.
	*	CDMG	6	Reported 18" of lateral offset.
	E. Hart	USGS	6	Lateral spreading; cumulative extension of 4m.
	A. Gillespie	CIT	7	Subsidence and/or compaction of road bed...asphalt cracks.
	J. Anderson & T. Heaton	USC & USGS @ CIT	8	Minor felt earthquakes every few minutes at Convict Lake through Monday.
	J. Anderson & T. Heaton	USC & USGS @ CIT	9	Ground cracking.
	C. Real	CDMG	9a	Lateral spreading.
	J. Kahle	CDMG	10	Ground cracks on the Hilton trend; strange slumping and discharge.
26 May 1980	J. Kahle	CDMG	11	Lurch cracks.
	C. Koesterer	USGS @ CIT		
	A. Gillespie	CIT	6	>18" locally, but slumping; some previous to 25 May (earthquake?).

<u>DATE</u>	<u>OBSERVER</u>	<u>ORGANIZATION</u>	<u>MAP REFERENCE</u>	<u>OBSERVATION/COMMENT</u>
6 May 1980	R. McJunkin	CDMG-SMIP		
	C. Turpen	CDMG-SMIP		
7 May 1980	W. Charleston	Associated Press		
	*	CDMG	12**	Road offsets and landslide; road closed.
	A. Gillespie	CIT	13	Laurel Creek - road settling but no direct faulting in line with Laurel Mt.-Lake Gennieve fault.
	A. Gillespie	CIT	2.	Fault cracks on road (across McGee moraine) maybe more extensive, offset maybe a little greater.
	A. Gillespie	CIT	15	Convict Lake minor shocks very frequent from 11pm - 2am (May 27) but quiet from approximately 4am to big shock at 8am.
	A. Gillespie	CIT	15	Nothing except lurch cracks, etc.
	G. Taylor	CDMG	16	Ground cracking of possible tectonic origin.
	G. Taylor	CIT	17	Linear cracks but no offset?
	A. Gillespie	CIT	18	Minor cracks at 7600-7800'.
	A. Gillespie	CIT	19-21	No effects.
	A. Gillespie	CIT	22	Very minor cracks...Convict Creek has continuous rumbling and shaking at 1730.
	S. Henry Mayeda	LADWP		
	F. Finkheimer	LADWP	23	
	E. Corbett	CIT-Seismo Lab	23	Displacement down on east along older scarp.
	*	CDMG	24	Displacement doubled (?) no measurement.

25
(omitted)

<u>DATE</u>	<u>OBSERVER</u>	<u>ORGANIZATION</u>	<u>MAP REFERENCE</u>	<u>OBSERVATION/COMMENT</u>
27 May 1980	G. Taylor	CDMG	26	Cracking in evidence; change from 26 May.
	J. Kahle	CDMG	27	Ambiguous cracks along older scar (may be settling cracks).
	U. Lamanuzzi	USGS & CIT	28	During earthquake of 27 May 1980 7:45am, Ed Corbett and I saw and hear preexisting cracks in the road floor vertically and horizontally and actually extend into the dirt shoulder about 6 inches. These preexisting cracks are perpendicular to the road trend and appear approximately regularly spaced.
	E. Hart	USGS	29	Lateral spread failures at Convi Lake campground. Fractures extend about 25m parallel to shore and extend about 10m back from the shoreline.
	R. Mueller	USGS	30	Observed dust in Valley after magnitude 6 on 27 May 1980.
28 May 1980	A. Gillespie	CIT	31	2½" offset - 15m scarplet, 21m below top of second scarp; site is N83.1° of intersection of old 395 and McGee Road; scarplet = 50 , scarp = 30. Also possible 4" offset SE of "TOW" road at same level.
28 May 1980	U. Lamanuzzi	USGS	32	Settlement cracks on road and by side of road.
			33-35 (omitted)	
	G. Taylor	CDMG	36	From air 6-10 inches vertical side down; flight to Davis Lake.
	G. Taylor	CDMG	37	Upper McGee Creek see nothing.

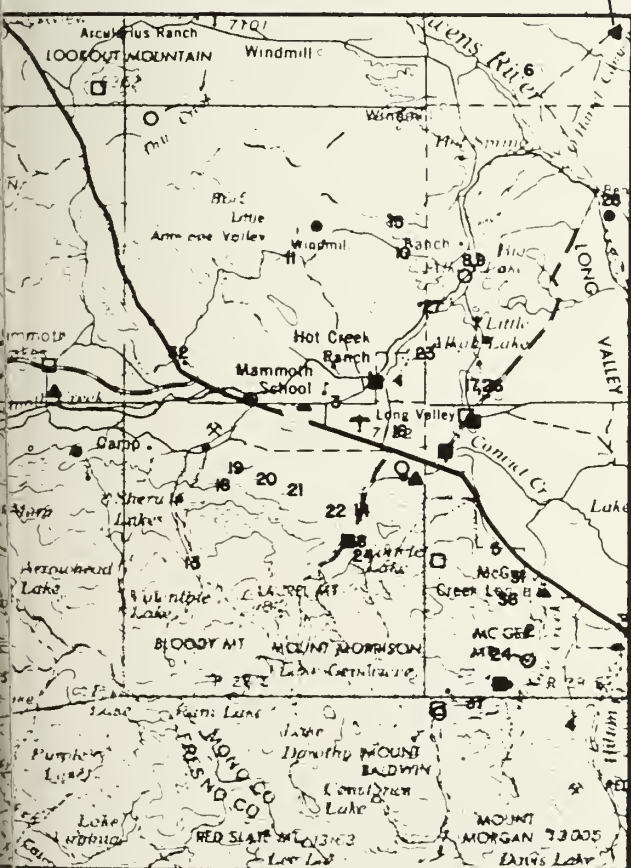
- * Origin of comment unknown, description above from CDMG clearinghouse staff.
- + Any words added for clarity will be followed by a question mark and enclosed in parenthesis.
- ** Along old Route 395 near BM 7208 on Casa Diablo Mtn. Quadrangle.
- ++ Dust clouds observed in Pine Canyon (Mt. Tom Quadrangle) from Route 395.

LEGEND

- Seismological Laboratory, University of Nevada
- Seismology Group, California Division of Mines and Geology
- ▲ Strong Motion Instrumentation Program, California Division of Mines and Geology
- U.S. Geological Survey (Menlo Park, CA)

At Glass Mountain
approximately 4km NE

- OR ■ University of Southern California, Los Angeles, CA and the U.S. Geological Survey at California Institute of Technology
- ▲ Civil Engineering, California Institute of Technology
- ◀ Seismological Laboratory, California Institute of Technology



- Approximately 5km east of map boundary
- ▲ Long Valley Dam approximately 4km E. of map boundary
- ▲ Whiskey Creek approximately ½ km E. of map boundary

118°45'

Figure 1. This figure locates approximately the reports of earthquake damage which were collected at the clearinghouse. Numbers refer to descriptions shown in Table 1 and the symbols identify either proposed or occupied seismic instrumentation sites.

CALIFORNIA DIVISION OF MINES AND GEOLOGY DISTRICTS



Figure 2. The telephone numbers necessary to locate the CDMG earthquake clearinghouses are shown in this figure together with the CDMG districts.

SURFACE RUPTURE ASSOCIATED WITH THE MAMMOTH LAKES EARTHQUAKES OF 25 AND 27 MAY, 1980

By

Gary C. Taylor and William A. Bryant
California Division of Mines and Geology

INTRODUCTION

A magnitude (M) 6.0 earthquake occurred near Mammoth Lakes at 9:33 am on May 25, 1980, the first of three M 6+ earthquakes to occur within a 48-hour period. The second event (M 6.3) occurred at 12:45 am on May 25 and the third (M 6.0) on May 27, 1980 at 7:50 am.

Aside from damage and other secondary effects caused by shaking, observed surface rupture generally occurred in the area bounded by Lake Crowley, the community of Mammoth Lakes, Lookout Mountain, and the Owens River. Within this area, surface rupture occurred along numerous north to northwest-trending late Tertiary faults.

Surface fault rupture associated with the Mammoth Lakes earthquakes was observed and mapped by the authors during the periods May 26-31, June 26-27, and July

7-11. Field mapping and observations during the period May 26-31 were also made by other California Division of Mines and Geology (CDMG) personnel Trinda L. Bedrossian, Earl W. Hart, James E. Kahle, and Richard D. McJunkin. Preliminary data were also contributed by U.S. Geological Survey (USGS) personnel M.M. Clark, J.C. Yount, P.R. Vaughan, J.C. Tinsley, and E.J. King. Observations by these contributors are compiled on Plate 1 and are gratefully acknowledged.

It was not possible to document all faults that may have had surface rupture due to the unconsolidated volcanic soils, alluvium and talus of the area and the rate at which evidence of surface cracking was destroyed by almost daily rain showers, winds, and animal activity. Additionally, an unusually large snowpack covered the higher elevations in the areas west and south of Mammoth Lakes, and although major mapped faults were checked

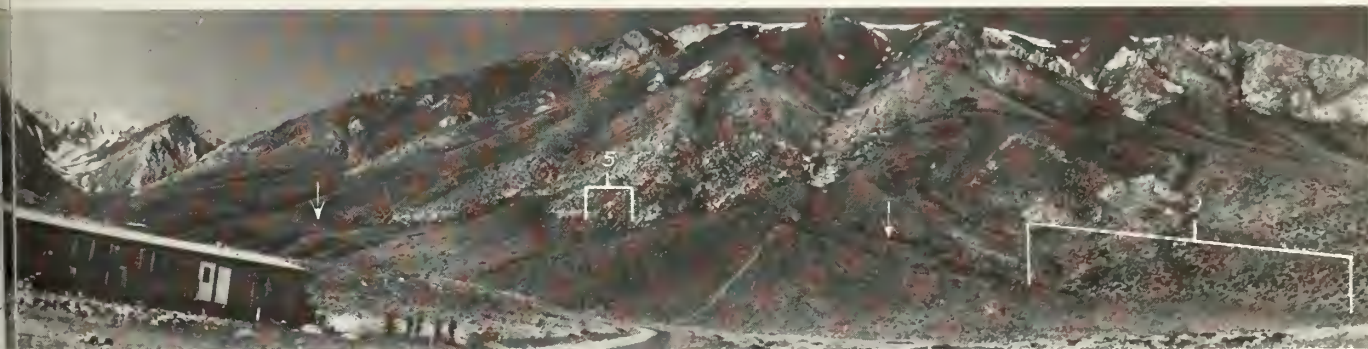


Plate 1. Panoramic view of Hilton Creek fault from McGee Creek Road, looking from south to west. Holocene east-facing fault scarps (indicated by arrows at base of scarp) offset colluvial deposits and Cretaceous granite on the east slope of McGee Mountain. Localities 5 and 9 (Plate 1) are shown for reference. (Distortion of trailer in left foreground due to wide angle of view.) Photos by W. A. Bryant unless otherwise noted.

by helicopter overflights, actual on-the-ground field checking was precluded.

Original field observations by several investigators (CDMG and USGS) are published in CDMG Open-file Report 80-12SAC (Bryant and others, 1980). Duplicate observations have been combined and edited by the authors and are presented in this report in the Tabulation of Observations. The fault traces observed in the field and traces identified on aerial photographs were transferred by the authors to the topographic basemap (Mt. Morrison 15' quadrangle) by use of a Bausch and Lomb Zoom Transfer Scope.

DESCRIPTION OF SURFACE RUPTURE

Surface fault rupture associated with the Mammoth Lakes earthquakes occurred principally as a discontinuous, distributive zone of fractures extending over a distance of approximately 20 km. Two distinct patterns of surface rupture were observed: (1) an essentially linear zone of north-northwest trending fractures along the Hilton Creek fault of Rinehart and Ross (1964) in the McGee Creek to

Convict Creek area, and (2) a wide, distributive zone of north and northwest trending fractures (Bailey and Koeppen, 1977) north-northwest of the intersection of Convict Creek and Highway 395.

Hilton Creek Fault

The Hilton Creek fault trends north-northwest from Hilton Creek through the southern boundary of the Long Valley caldera (photos 1 & 2). The narrow zone of east and northeast-facing fault scarp that define the Hilton Creek fault as major structural escarpment terminate at the caldera boundary; within the caldera it splinters into several minor divergent faults that have little surface continuity northward. Thus, for purposes of clarity in this article, the northern extent of the Hilton Creek fault is defined to be along the discontinuous faults that define out approximately three-quarters of a mile north of Whitmore Hot Springs near the midpoint of section 31.

Surface fractures along the Hilton Creek fault were first noted in the McGee Creek area by CDMG seismologist Chris Cramer on May 25. The southernmost evidence of surface rupture along the

Photo 2. McGee Creek moraine; view looking south. The Hilton Creek fault ruptured from the valley of McGee Creek northward along the slightly arcuate trend of east-facing scarps. Arrow indicates top of scarp.



Hilton Creek fault occurred along the well-defined northeast-facing scarp crossing the crest of the lateral moraine (Tioga Stage) immediately southeast of McGee Creek. Cracks with approximately 10 cm of extension and 10 cm of vertical offset (down to the northeast) were observed at this location (M. Clark, SGS). Vertical displacement across McGee Creek Road (10 cm, down to the northeast) was probably enhanced by slumping of road fill (photo 3). Surface rupture across the northern lateral moraine of McGee Creek (Tioga Stage) occurred in a 0.3-3 m wide zone of multiple cracks along the upper one-third of the existing 15 m-high northeast-facing scarp.

Two zones of cracking in colluvial material were observed north of McGee Creek Road to the southern boundary of section 20. The westernmost zone, typically 1-5 m wide, was comprised of a main break with measurable vertical displacement (5-20 cm, down to the east) flanked by cracks with smaller offset (1-3 cm). The smaller cracks generally occurred downslope from the main break, although some minor cracking was observed upslope from the principal rupture. Within this segment, the trend of the rupture zone was generally N15°W, with net slip vectors in a N45°E direction.

An abrupt change in trend and character of surface rupture occurred near the southern boundary of section 20. The trend changed to N15°E and cracking was typically confined to single traces with 1-2 cm of extensional opening with no measurable vertical component. This trend continued to near the mid-point of section 20 then returned to a bearing of N15°W.

North of section 20, surface rupture generally occurred in a zone from 2-20 m wide with 1-30 cm of vertical offset (east side down) along the 20-40 m high existing east-facing fault scarp (photo 4). Near the intersection of the Hilton Creek fault and Highway 395, surface rupture consisted almost entirely of extensional cracking with little, if any, measurable vertical offset. However, at one location

immediately south of the highway, a vertical component of 1 cm with a slip vector of N85°E was noted.

Projected Trace of Hilton Creek Fault

The style and character of surface rupture changes abruptly just north of



Photo 3. Surface rupture on the Hilton Creek fault; view north. A single break across McGee Creek Road with about 100mm of vertical displacement, east side down, was enhanced by slumping. Vertical displacement of 70-80mm occurred along the upper third of the scarp on the northern lateral moraine of McGee Creek (refer to locality description 1). Photo by R. D. McJunkin, May 26, 1980.

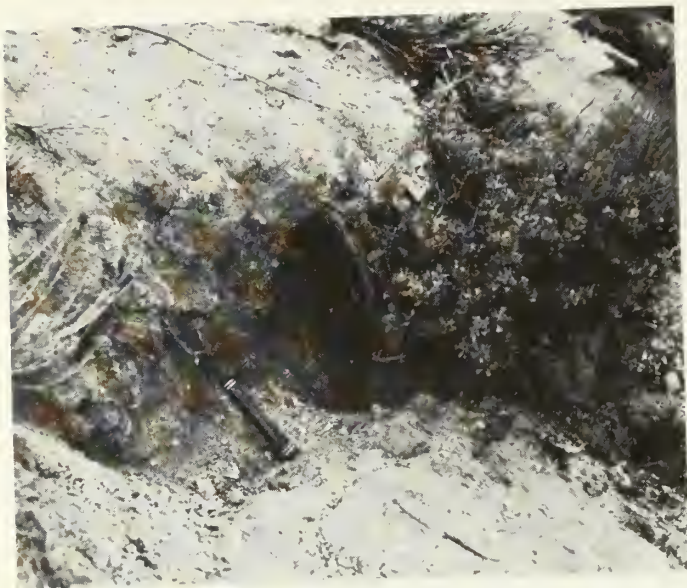


Photo 4. Surface rupture along Hilton Creek fault. Vertical offset of about 270mm, down to the east, was the maximum observed along this fault. An undetermined amount of slumping has enhanced the vertical displacement. Note hammer for scale. Photo taken May 28, 1980.

Convict Creek along the northern projection of the Hilton Creek fault into the Long Valley caldera (Plate 1). Both Rinehart and Ross (1964) and Bailey and Koeppen (1977) locate the southern rim of the caldera in the Convict Creek-Tobacco Flat area, and the intracaldera structure undoubtedly becomes the major factor in controlling surface rupture north of this juncture.

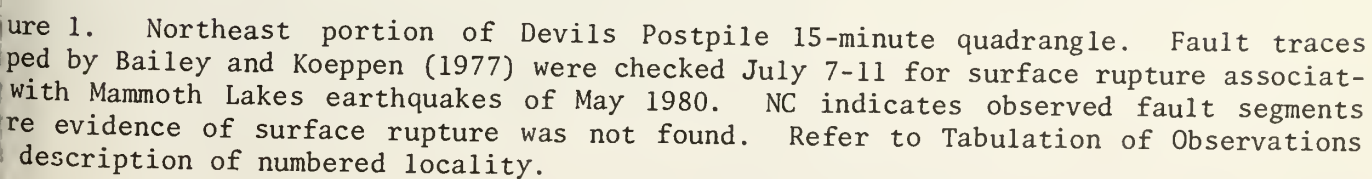
Surface rupture along the projected trace of the Hilton Creek fault between Convict Creek and Whitmore Hot Springs (SE 1/4 of section 6) was comprised of very discontinuous cracks with 1-2 cm of extension. Immediately northwest of Whitmore Hot Springs, surface rupture occurred along two sub-parallel traces: an eastern zone, 100-150 m wide, with minor cracking, and a well-defined zone of cracks coincident with an existing east-facing scarp approximately 275 m to the west. Surface rupture was continuous along this trace for approximately a kilometer to the north.

Additional surface rupture was observed along other Quaternary faults near Whitmore Hot Springs. Generally, cracking was very discontinuous with little, if any, vertical displacement. However, mappable surface rupture occurred along a northwest-trending fault northwest of Whitmore Hot Springs (Plate 1, locality 33).

"Mammoth Airport Fault Zone"

Surface rupture occurred along a major northwest-trending graben structure informally referred to in this article as the "Mammoth Airport fault zone". This fault zone is comprised of northwest-trending faults that form a major graben (Plate 1; northwest from section 1, T4S, R28E; and northwest from section 34, T3S, R28E). The graben is bounded on the southwest by a complex zone of east and west-facing fault scarps forming a series of minor graben structures. The main graben is bounded on the northeast by a continuous series of southwest-facing fault scarps trending N40°W.

The southeastern extent of the northeastern boundary of the graben creates a prominent ground water barrier immediately northwest from the intersection of Whitmore Hot Springs Rd and Highway 395. This fault passes east of the airport along a well-developed southwest-facing scarp which offsets a basalt flow. Minor extensional cracking, 1-10 mm, occurred along a zone 1-1.5 m wide, generally coincident with the base of the pre-existing scarp but occasionally near the crest along this trend northwestward to and across Hot Creek. Discontinuous, but significant cracking (5-10 cm of extension with occasional vertical offset to 1 cm) developed along this southwest-facing scarp. Two localities (#48 & #49, Plate 1) were documented as showing right-lateral extension of 1.5-2.5 mm and 20 mm, respectively, along this zone of cracking. Surface fractures extended northwest from Hot Creek for about 7 km. Thus, the total



length of discontinuous surface rupture along the northeastern boundary of the "Mammoth Airport fault zone" was about 10.5 km.

Major surface rupture also occurred along the southwest boundary of the "Mammoth Airport fault zone". Maximum vertical offset along this trend was 25-30 cm, down to the east, with 10-15 cm of extension (Plate 1, locality 95). Surface rupture typically occurred along the base of the pre-existing scarps, but was occasionally observed in back of the crest of the scarp (warping). Cracking was also noted within the intra-graben areas, not coincident with any pre-existing scarp. It was apparent that particularly intense ground shaking occurred in this area (section 28), evidenced by abundant rockfalls, landslides, and shattered pine trees. Surface rupture along faults near mapped fumaroles occasionally had steam issuing from the cracks. Some of the vents along the fault were either new or recently reactivated, based on the dead and dying vegetation near the vents (Plate 1, locality 95).

Other Northwest-trending Faults

Northwest-trending faults adjacent to and north of Casa Diablo Hot Springs (NW 1/4 of section 32) were found to have minor extensional cracking (Plate 1). Cracking in this area was very discontinuous and subtle. The northernmost occurrence of surface rupture was located 5.1 km north of Casa Diablo in section 18.

Minor extensional cracking occurred west of the main trend of surface rupture along north-trending faults associated with the Inyo Craters. Cracking was observed along the "Earthquake fault", a north-trending fissure located about 3 km west of Mammoth Lakes. Although most of the cracking along the "Earthquake fault" was the result of seismic shaking, a minor crack approximately 300 m in length with about 1-2 mm of vertical offset (down to the west) was probably tectonic. Cracking also occurred along a prominent east-facing fault scarp located northeast of the "Earthquake fault" (figure 1). It was not clear whether this cracking was

Photo 5. Surface rupture in tuff beds located about 1.6 km north of Whitmore Hot Springs; view looking west. Vertical offset of about 20 mm (down to west) occurred along this fault. Refer to locality description 22. Photo taken May 29, 1980.



result of fault rupture or seismically-induced settlement. Cracking along this fault was confined to the bedrock-talus contact along the margins of vertical scarps in bedrock. No cracks were observed along the fault scarp north or south of the vertical scarp in bedrock.

POST EARTHQUAKE MOVEMENT

Field observations indicate that surface rupture resulted from the two principal events on May 25, possibly enhanced by the larger aftershock sequence of the same day. With one exception, it was not possible to relate surface rupture with a specific event. Extensional cracks of about 5 mm along a small northwest-trending graben structure measured May 26) increased to approximately 6 cm following the May 27 M 6.0 event (photo 5; Plate 1, locality 22). Afterslip was discounted since features indicative of ground shaking (disrupted colluvium, rotated and disjointed blocks of flat lying tuff) were observed on May 27, but not on May 26. Several fault localities were checked for afterslip by the authors on June 26-27 and July 7-11, but no additional movement was noted at any locality. Evidence of afterslip is generally difficult to document except where fault traces cross paved roads or where rupture has occurred in bedrock. The loose, bouldery morainal and colluvial material along the Hilton Creek fault and the loose, often deep tephra covering a large portion of Long Valley caldera will not preserve evidence of afterslip.

DEGRADATION OF SURFACE RUPTURE

Evidence of surface rupture associated with the earthquakes of May 25 and 27 was rapidly destroyed in most localities by either, animal activity, and the generally unconsolidated surficial deposits in the area. In some areas, rapid infilling of cracks hindered the mapping of surface rupture immediately after the large earthquakes. Thus, measurements of displacement were only approximate in

areas subject to degradation after about May 28.

Evidence of surface rupture was almost completely destroyed in most areas by the first week in July. Cracks along the Hilton Creek fault at McGee Creek Road were destroyed (Plate 1, locality 1) and no evidence of surface rupture was observed across the northern lateral moraine. Farther north, near locality 2 (Plate 1), surface rupture in loose, bouldery colluvium was expressed as a very subtle, discontinuous trough, the result of the inward collapse of near-vertical fissure walls and subsequent in-filling of the fissure.

Selected areas where surface rupture was flagged during the field investigations in May (such as localities 28-50, Plate 1) were revisited in June and July by the authors. Generally, the evidence of surface rupture was completely destroyed, or was so subtle and discontinuous that a distinction between animal activity and cracking could not be made. However, a few areas did retain cracks in a relatively pristine state because of a more cohesive quality of the surficial materials. Areas that retained evidence of surface rupture, at least through the first week in July, included localities 22, 77, and 95 (Plate 1).

SLUMPING

Ground failure caused by shaking associated with the Mammoth Lakes earthquakes occurred in several locations in upper Long Valley. In addition to numerous road and other artificially emplaced fills, major slumping was prevalent at Little Antelope Valley, along margins of the Owens River in upper Long Valley, along northwest margins of Lake Crowley, and along Hot Creek meadow.

Slump cracks typically developed at the interface between water saturated alluvial sediments and colluvium. The soft and loose saturated volcanic soils have sufficiently low strength under static

conditions to account for the downslope ground movement during strong shaking. At several locations impressive cracks 12-35 cm wide and 60-100 cm deep developed on the margins of meadows. Minor sand boils associated with some of the slump cracks suggest that liquefaction locally was a contributing cause of slumping.

SUMMARY AND DISCUSSION

Principal observed surface rupture associated with the Mammoth Lakes earthquakes occurred along a broad zone of north-northwest trending Quaternary faults within the boundaries of the Long Valley caldera and southeastward from the caldera along the Hilton Creek fault (Plate 1). Collectively, surface rupture occurred within a zone at least 20 km long by up to 10 km wide.

The pattern of faulting within the Long Valley caldera is complex, with numerous branching and subsidiary traces showing extensional surface rupture along, but not limited to, Quaternary fault scarps (Plate 1). Discontinuity of mappable surface fractures along known faults (Bailey & Koeppen, 1977 and Rinehart & Ross, 1964) was commonplace because the unconsolidated volcanic soil of the area was not conducive to either the creation or preservation of surface cracking. Most of the linear crack zones not associated with known faults had very short lengths with extensional displacement and appeared to be of minor structural importance. Maximum measured vertical offset of almost 30 cm occurred along an east-facing fault scarp (Plate 1, locality 95). This fault forms part of the southwest boundary of the "Mammoth Airport fault zone", a major northwest-trending graben within Long Valley caldera. Total vertical displacement probably exceeded 30 cm because offset was distributed over several sub-parallel normal faults within the graben.

Surface rupture along the Hilton Creek fault generally occurred as linear zones of discontinuous open cracks, commonly

enhanced by downslope movement and typically coincident with Holocene fault scarps. The sense of offset was normal, with a dip-slip component of down to the northeast. The measured maximum vertical offset for ground fractures along the Hilton Creek fault between Highway 395 and McGee Creek was 27 cm. Ground observations suggest that vertical offset though locally enhanced by down-slope movement, was frequently distributed over a zone 2-20 m wide and, therefore, total vertical displacement may be somewhat greater than measured.

Observed surface rupture within the intracaldera region and along the Hilton Creek fault indicates that the region underwent east-west to northeast-southwest extension. However, the pattern and style of surface rupture does not seem to conform with results of first motion studies (see Cramer, accompanying article). Briefly, first motion analyses for the 3 $M \geq 6.0$ events indicate that fault rupture occurred along either: 1) a near-vertical north-south trending fault with left-lateral strike-slip displacement; 2) a steeply north dipping east-west trending fault with right-lateral strike-slip displacement. In contrast, fault plane solutions of some earthquakes within the larger $M \geq 4.0$ aftershock sequence show normal solutions indicating these earthquakes were caused by crustal extension. These data support the observed surface rupture associated with the May 25 and 27 events and Quaternary geologic evidence within the region.

Possible tectonic models postulated by the authors as causative for the May 1980 seismicity include: 1) principal rupture along the Hilton Creek fault; 2) principal rupture along a previously unrecognized north to northeast trending left-lateral strike-slip fault; and 3) principal rupture along the east-west trending southwest margin of the Long Valley caldera.

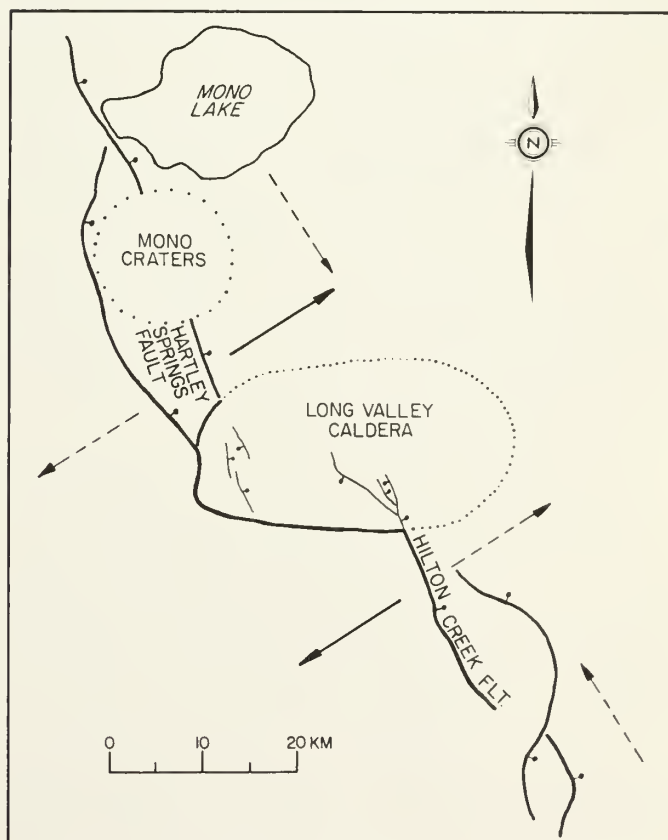
1) It is tempting to assume that the causative fault of the May 1980 earthquake sequence was the Hilton Creek fault. However,

fault is a part of the Sierra Nevada frontal fault zone, and continuous surface rupture was documented as occurring along Pliocene scarps associated with the Hilton Creek fault. Geologic evidence indicates that the Hilton Creek fault dips to the east and that major vertical offset (downthrown block to the east) has occurred since Pleistocene time (Rinehart and Ross, 1964). However, this model is complicated by the fact that the epicenters of the three principal $M \geq 6.0$ events are located west of the east-dipping Hilton Creek fault. Additionally, the majority of the $M \geq 5.0$ aftershocks also have preliminary epicenters west of the Hilton Creek fault with no indication of linearity along a north-south trend. This data implies that if a normal fault is responsible for the May 1980 seismic activity, its surface trace must be west of the Hilton Creek fault within the Cretaceous granitic rocks. No faulting has been documented as offsetting these Mesozoic granitic rocks

in this area, although careful ground checking was not possible following the May 1980 earthquakes.

2) The tectonic framework along the eastern Sierra Nevada has generally been extensional. Strike-slip components along some normal faults have occurred (Whitney, 1872; Gianella, 1959; Bonilla, 1968), although cumulative lateral displacement along these faults has been minor (Christensen, 1966). Left-lateral strike-slip displacement along a north to north-northeast trending unmapped fault is problematic. Previously mapped faults near the May 1980 epicenter locations do not offset Mesozoic age plutonic rocks, and observation by helicopter on May 28 did not reveal evidence of surface rupture along the epicenter trend. Evidence of strike-slip displacement was not observed along the majority of fault traces along which surface rupture occurred, and was a very minor component along the northeastern boundary of the "Mammoth

Figure 2. Tectonic map of Long Valley-Mono Basin area. Sierra Nevada frontal faults (including Hilton Creek and Hartley Springs faults) are emphasized with heavy line (ball on downthrown side); post-caldera faults within Long Valley caldera are shown with lighter line. Stress axes (indicated by arrows) are derived from fault plane solutions of selected foreshocks and aftershocks of the May 25 and 27, 1980 Mammoth Lakes earthquakes (see Cramer, accompanying article). Extension directions depicted by solid arrows emphasize orientation of couple in relation to south caldera boundary fault. Compressional axes are oriented perpendicular to extensional axes. Modified from Bailey and others, 1976.



Airport fault zone" (Plate 1, localities 48 & 49). The strike-slip component that was observed was almost totally right-lateral along north to northwest trending faults. Right (and left) lateral strike-slip components observed across the northern lateral moraine of McGee Creek (USGS; Plate 1, locality 1) probably were the result of slumping toward free faces along the lateral moraine.

3) The Long Valley caldera is a major influence in local response to regional tectonic stress. Dip-slip (down to the east) displacements within the caldera are significantly less than displacements along Sierra Nevada frontal faults northwest and southeast of the caldera, indicating that displacements have somehow been distributed within the caldera.

Locally, vertical displacement along the Hilton Creek escarpment may total 1100 meters since Pleistocene (McGee stage) time (Rinehart and Ross, 1964; Bailey and others, 1976). Northwest along the frontal fault system, the Hartley Springs fault offsets Bishop tuff (0.7 my) by about 300 m. Both of these faults terminate at the boundary of the Long Valley caldera (figure 2). The projected trace of these faults continues into the caldera principally as en echelon faults with relatively minor vertical offsets. Along the western margin of the caldera, north trending faults aligned with the Inyo Craters offset 0.2 my-old trachyandesites by about 15 m, 0.1 my-old rhyolite by about 10 m, and 650-yr old Inyo Craters phreatic deposits by about 5 m (Bailey and others, 1976).

Displacements and youthful geomorphic features suggest that movement along the projected trace of the Hartley Springs fault has occurred during Holocene time. Similarly, the Hilton Creek fault south of Long Valley caldera displaces Tioga-stage glacial deposits by about 15 m. Geomorphic expression of the Hilton Creek fault as a prominent escarpment terminates at the caldera margin where the essentially linear trace of the Hilton Creek fault splinters into several traces

along a north to northwest trend. The most prominent and continuous trend along the projected trace of the Hilton Creek fault offsets 0.3 my-old rhyolites by about 15 m as well as 0.6 my-old to 0.7 my-old rhyolites, indicating that displacements are relatively contemporaneous with post-Tioga displacement south of the caldera (Bailey and others, 1976).

Bailey interpreted that post-caldera displacement was accommodated along the east-west trending southwest caldera boundary fault which apparently truncate morainal ridges of Mono Basin age in the Laurel-Sherwin Creek area. north-trending fault paralleling the west caldera wall truncates the northeast face of Mammoth Mountain. In contrast, the east and north walls of the caldera show no evidence of post-caldera movement (Bailey and others, 1976). Thus extensional offset occurring along the Hilton Creek trend may have stepped later to the Hartley Springs trend along the south and west margins of Long Valley caldera during a period when the Long Valley magma chamber was shallow and its roof thin and weak (Bailey and others, 1976). As the magma chamber cooled, faulting developed across the caldera sub-parallel to the projected traces of the Hilton Creek and Hartley Springs faults.

The foreshock activity (Cramer, accompanying article) and the first $M \geq 6.0$ events are closely coincident with this southwest caldera boundary fault. Focal plane solutions indicating right-lateral displacement along an east-west trend are compatible with fault rupture along an east-trending fault in response to northeast-southwest extension. Furthermore, this suggestion is reinforced by preliminary aftershock data ($M \geq 0$) that indicates a spatial association with the southwest caldera boundary along an east-west trend.

Geomorphic expression of this fault is very weak or non-existent along the southwest margin of the caldera, indicating

vement along this fault probably has not occurred since mid to late Pleistocene time. Additionally, evidence of surface rupture was not observed along this trend associated with the May 1980 earthquakes.

The three tectonic models advanced by the authors all have inherent problems in explaining the seismic events of May 1980. The observed surface rupture, irregular topography, contrasting lithology, and fault mechanisms derived from geosismological calculations indicate that complex tectonic processes are deforming the Mammoth Lakes region. Thus, detailed local plane studies on a regional basis and detailed analyses of both foreshock and aftershock sequences are necessary in order to adequately evaluate the causative tectonic processes and the local influence and response of the Long Valley caldera to these processes.

KNOWLEDGEMENTS

This article was reviewed by Earl W. Hart, John T. Alfors, and Tousson R. Lopezada of the California Division of Mines and Geology.

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TABULATION OF OBSERVATIONS

The numbered observations correspond to locations depicted on Plate 1. The majority of field observations were made by CDMG personnel May 25 through May 31, 1980. Additional observations by CDMG and USGS personnel were made June 1 through June 4, June 2 and 27, and July 7 through July 11, 1980 and have been incorporated onto Plate 1.

1. Surface fault rupture along east-facing scarp of the Hilton Creek fault. Vertical offset at McGee Creek Road ranged from 50mm at the inner part of the road to 100mm along the part of the road nearest the free slope; both displacements east side down. The offset nearest the free-face has been enhanced by slumping of road fill. After the M6.0 event on 5/27/80, surface rupture may have increased by a few centimeters. Southeast of McGee Creek Road multiple cracks in a zone from 0.3m to 3m wide occur near the top of the Hilton Creek fault scarp. Offset ranged from 50mm to 150mm, down to the east. The southernmost extent of surface rupture along the Hilton Creek fault occurred at the top of the southern lateral moraine of McGee Creek. About 110mm of extension and 110mm of vertical offset (down to E) were observed (USGS). Fault rupture from McGee Creek Road NW to the crest of the lateral moraine generally occurred along the upper third of the fault scarp. Vertical displacement ranged from 70mm to 80mm, down to the east (USGS).

2. Very steep slope with E-facing scarp in loose colluvium. Discontinuous cracks with maximum vertical offset of 50mm (down to E) and extension. Cracks partly enhanced by shaking and downhill movement.

3. Surface rupture along E-facing scarp. Zone of cracks is 2m to 5m wide (USGS) and trends N20W. Extensional component of cracks is 80mm; vertical offset is 150mm.

4. Surface rupture observed along E-facing Holocene scarp of Hilton Creek fault. Cracks trend N15W and measured vertical offset along crack is about 140mm, down to the east. Some degradation of scarp had occurred; rupture occurred in colluvium, light yellow brown gravelly silt with minor amount of clay.

5. Surface rupture along Hilton Creek fault. Trend of rupture same as 4. Maximum vertical displacement was observed at this location: about 270mm of vertical offset, E side down. Average vertical displacement observed was about 19mm. It is not known what amount of this displacement is due to surface fault rupture and what amount is due to seismic induced slumping.

6. A zone of cracks 5m to 6m wide was observed at this location. This zone characteristically was comprised of a large break with measurable vertical displacement (~120mm) flanked by cracks with smaller offset, generally downslope from the major break, although some cracking was observed upslope from the principal rupture. The smaller cracks generally were extensional with little (<5mm) to no vertical offset. The trend of the rupture zone was generally N15W, but at one point changed to N10E (heading downslope) for about 30m, then changed trend to N15W up to, but not on or beyond the northernmost bench south of locality.

7. Surface rupture along Hilton Creek fault. Vertical displacement measured 180mm to 250mm, down to the east. Downslope movement due to shaking is likely.

8. NE-facing 21m-high scarp in loose bouldery soil. Allan Gillespie (Caltech 5/28/80) reported 60mm of vertical offset (down to east); partly verified by Hart, 6/27/80. Boulders rolled down from scarp during earthquakes.

9. Discontinuous surface rupture along a general trend of N20E. Cracks are extensional, with from 5mm to 20mm offset. No vertical offset (USGS).

10. Well-defined NE-facing scarp. north

with extensional opening of 20mm occurred in a zone 1m to 5m wide (USGS).

1. N20°W-trending zone of cracks 3-20m wide along a 20-40m high pre-existing, E-facing scarp in older moraine deposits. Maximum extensional opening and vertical offset (down to east) of 20mm to 30mm on individual cracks in loose soil. Vertical offset greater locally, but probably enhanced by sliding.

2. Barbed-wire fence offset and snapped due to downhill movement (mostly land-sliding?) of 1m± on steep E-facing scarp on moraine; some cracks with vertical offset, down to east.

3. Extensional cracks about 17mm wide across U.S. Highway 395; no vertical offset. Crack zone trends N10-15W; individual cracks vary to N40W. Highway is built in fill at this location and cracking may be a result of seismically-induced settlement. However, cracks can be traced to the south beyond the highway. Cracks south of Highway 395 trend sub-parallel to old Highway 395 and extend into natural material (CDMG). Crack zone south of old Highway 395 is about 0.5m wide with vertical displacements of about 10mm, down to east (USGS).

4. Continuous crack trending N45W. Vertical offset is 76mm, down to the east. South end of crack curves east near the edge of a gravel pit and may be the result of slumping.

5. Discontinuous extensional cracks (about 1.5mm to 3mm wide) trend N40W immediately west of a gravel pit. Vertical displacement along this trend was about 2m, down to the east.

6. Broad zone of extensional cracks and subsidence in Highway 395. Slump cracks across S. bound lanes of Highway 395 due to low-angle slide in saturated material. These cracks are probably caused by liquefaction since sand boils and ejected mud occur along the cracks in median strip of highway. Westernmost cracks have right-

lateral offset of a few centimeters, and can be traced along the median strip. The cracks cross back over the S. bound lanes with minor disruption of paving.

17. This fault trace observed from helicopter on May 28, 1980. Cracking was observed along a buried pipeline that was coincident with a subtle E-facing fault scarp of Rinehart and Ross (1964) (CDMG). Extensional cracks along this trend were 10mm to 30mm wide. No vertical displacement was observed (USGS).

18. Extension cracks about 2.5mm to 5mm wide, located about 4.5m upslope on a N30W trend. To the south the cracks were not observed in Whitmore Hot Springs Road. Cracks were traced for about 30m south of Whitmore Hot Springs Road along the general trend of the fault.

19. Zone of cracks up to 100m wide along subtle E-facing scarp. Cracks are discontinuous with extension of 3mm to 6mm and about 6mm of vertical offset, down to the east. Total vertical displacement is probably 20mm to 50mm over several sub-parallel cracks.

20. Zone of cracks along well-defined W-facing fault scarp. Trend of scarp is N35W. Extensional opening of cracks ranges from 12mm to 25mm. Vertical offset is from 6mm to 12mm, west side down. Cracks occur along the crest and slope of the fault scarp. Cracks are continuous for about 700m, then become discontinuous beyond old refrigerator on dirt road.

21. Zone of cracks along E-facing scarp NW of Whitmore Hot Springs. Individual cracks have extensional opening of 10mm to 20mm with vertical displacement of about 10mm, down to the east. Total vertical displacement over several cracks is less than 50mm. Width of crack zone ranges from a few meters to about 100m.

22. Surface fault rupture in tuff. Cracks associated with W-facing fault scarp and spring. Trend of cracks generally N30W, but locally is N45W. Extensional opening

of cracks was about 6mm to 12mm before M6.0 event of May 27. After May 27 earthquake extensional opening increased to about 60mm to 90mm. Vertical offset of about 20mm (down to W) occurred locally. Total length of crack zone is about 300m±.

23. Discontinuous cracks along SW-facing scarp; crack zone trends N30W. Maximum vertical offset of about 10mm to 20mm (down to SW) and maximum extension of about 5mm to 10mm was observed. Sinter deposit on vegetation indicates very recent geyser activity just west of road and west of scarp.

24. Hairline cracks observed along fault trending N30W. Cracks are discontinuous and can be traced for only about 15m to 20m.

25. Cracks coincident with E-facing scarp. Extensional cracks measured 6mm to 12mm, no vertical offset. Crack zone extends for about 100m. About 300m SE of road another zone of small cracks occurs along a pre-existing E-facing scarp. Opening of extensional cracks increased somewhat after May 27 earthquake.

26. Linear graben trending N15W has two small 6mm to 12mm sub-parallel cracks developed on E-facing scarp. Cracks traceable for about 50m.

27. Set of 3 small (3mm to 6mm) sub-parallel cracks 7.5m to 9m long that trend N30W and cut through a saddle. Apparent vertical displacement of 3mm, east side down.

28. Left-stepping cracks crossing dirt road on N10W trend. Crack zone traced for 60m to south but unable to trace to north along several slope breaks.

29. Surface rupture about 6m up on E-facing scarp. Small, sub-parallel extension cracks (3mm to 6mm) have about 3mm to 6mm of vertical offset, east side down. Trend of crack zone is N25E.

30. Surface rupture along same general

trend as 29. Two sub-parallel cracks trend about N10E. Cracks have vertical offset of 6mm, down to the east, and extension of 6mm to 12mm.

31. Surface fault rupture along N30W-trending E-facing scarp. Cracks occur along top of scarp or about halfway down. Vertical displacement along cracks is 25mm to 50mm, east side down. Extension averages about 25mm. Right-stepping cracks occur along base of the fault scarp. Fault rupture was continuous for about 1.3km.

32. Fault rupture. Six meter wide zone of right-stepping, en echelon tension cracks with less than 15mm of separation on average. As many as 6-10 cracks occur on any transect normal to trend of crack along older fault scarp.

33. Fault rupture. Maximum vertical offset along trace of older fault scarp is about 130mm, down on SW. Fault rupture strikes N05W, dips 30°-40° S. Vertical component approximately 60mm, extension about 110mm. No lateral component.

34. Minor zone of cracks trending N45W along bedrock high, possibly an old scarp. Zone is 10m to 20m wide and could be followed for about 100m south of road and north of road. Cracks are primarily extensional with less than 10mm of separation, many only hairline cracks in surface. Visited on 5/29/80, and most cracks obliterated by rain and wind on 5/28/80, but few were still visible.

35. Surface rupture along base or part way up face of older 2-8m high, SW-facing scarp. Scarp trends N30W. Cracks are extensional with occasional vertical displacement, down on SW. Displacements generally less than 10mm. Zone is intermittently continuous but seems to disappear to SE.

36. Surface rupture along NE-facing fault scarp trends N35W. Vertical displacement along crack zone is 12.5mm to 25mm, down to NE.

Surface rupture along SW-facing fault scarp. Cracks have vertical offset of 6mm to 12mm, west side down, with extension of about 3mm to 6mm. This fault scarp forms east side of graben described in 36.

Surface rupture along subtle SW-facing fault scarp. Cracks step both right and left across small dirt road east of airfield road. General trend of crack zone is N45W. Slight component of right-lateral extension (1.5mm) was observed.

Narrow zones of open cracks along base of well-defined, SW-facing scarp in the Pleistocene basalt flow and younger alluvium. Maximum vertical offset is 20mm (down to SW), but mostly just extensional opening. Cracks traced about 250m SE of gravel pit.

Small continuous cracks coincident with SW-facing fault scarp. Cracks trend N45W. Extensional opening of cracks about 5mm with a minor amount of vertical offset, west side down. Cracks generally occur along top of the fault scarp.

Small cracks across gravel road. Cracks trend N45W and are associated with subtle SW-facing fault scarp. Cracks are right-stepping of cracks observed on W side of road. 2.5mm of extension and about 2.5mm of apparent right-lateral displacement; no vertical displacement.

Small cracks associated with SW-facing fault scarp. Apparent vertical displacement of 8mm±1mm, W side down. Vertical displacement questionable because of steep "over slope" where displacement was measured. No vertical displacement observed SE of this location.

Small cracks on east side of gravel road trend N40W. Vertical displacement is about 3mm SW side down, with extensional opening of about 3mm. Cracks are discontinuous.

Small cracks with extension of 2.5mm and right-lateral(?) component of 1mm. Cracks trend N30W at this location.

45. Extensional cracks located about 1m up on fault scarp. Trend of cracks about N10W. Extension of cracks is about 4.0mm, with no vertical or lateral component.

46. Extensional cracks associated with well-defined SW-facing fault scarp. Cracks occur in zone about 4.5m wide. Easternmost crack in this zone has extension of 7mm and vertical displacement of about 10mm, down on W. Cracks occur along the base or slightly up on the scarp.

47. Extensional cracks across Hot Creek-Mammoth School road. Cracks extend NW and SE across base of SW-facing fault scarp. Several sub-parallel cracks trend about N15-20W over a 3m to 4.5m wide zone across the gravel road. Extensional opening of cracks varies from 12mm to 64mm. Southeast from the gravel road surface rupture generally occurs along the base of the fault scarp. Cracks here have extension of about 5mm with minor vertical offset of about 1mm, down to the SW.

48. Zone of cracks with a N50W trend. Cracks, which are primarily right-stepping, have a slight right-lateral extension of about 1.5mm to 2.5mm. A mini-graben with vertical offset of 7.5mm to both SW and NE and extension of about 6mm also occurs within the crack zone.

49. Zone of NW-trending cracks, at base of two SW-facing scarps in road, can be traced NW of road about 100m. Cracks are left-stepping in road at NE scarp, and up to 20mm of right-lateral extension measured W of road. Most cracks show only extensional opening. Rain has partly obliterated cracks.

50. Damage to Mammoth School (elementary) minor to moderate; appears to be due mainly to differential settlement of fill (sandy?) over an uneven, somewhat cavernous basalt lava. The lavas constitute the south margin of a large closed depression that is partly bounded by faults on the E and W. Tension cracks, settlement and some piping of fill largely pre-dates the recent earthquakes. Structural damage to

school was reportedly not major (Don Westbrook, OSA, 5/29/80). Some slumping of fill margins towards the drainages of Hot Creek occurred and the presence of numerous open cracks and sand boils (N65E trend) (one locality) suggest some liquefaction. Damage mainly due to falling objects (light fixtures, ceiling tiles, ventilation outlets). An increase in spring flow was reported in creek on N side of school. State Fish Hatchery to E, which is entirely on alluvium, did not appear to have any significant ground failure. Some minor NW-trending faults lie to the W and NW of the school as groundwater barriers in Hot Creek, but these do not trend toward the school. Another set of NW-trending faults occurs at the east end of the hatchery and appears to offset Hot Creek. This may align with hot springs and faults to the NW.

51. Faulting is distributive in this area. Discontinuous cracks trend N35-40W-extensional with no vertical displacement. One set of cracks associated with NE-facing scarp and small (10m to 15m diameter) closed depression. Extensional opening about 5mm. Another set of cracks east of this location associated with fault in tuff beds. Trend of this crack zone N40W. Surface rupture in this soft granular material has healed rapidly after rain of May 28.

52. Crack zone trends N60W. Cracks discontinuous, with extensional opening of about 5mm - estimated due to extensively modified cracks.

53. Hot spring - standing water level seems to have dropped about 1m, based on the extent of wet, clayey area around water.

54. Cracks associated with SW-facing fault scarp. Trend of crack zone N40W. Extensional opening of cracks about 7mm-8mm, no vertical offset. Cracks are discontinuous, but could be followed for about 600m.

55. Site of large boulder that bounced downslope during earthquake. Boulder measured about 7.6m x 6m x 4.5m. Series of

pits (generally 1m deep) were formed as boulder bounced downslope - one very deep (2.1m to 2.4m) pit was formed near base of slope.

56. Extensional cracks about halfway up steep slope mapped as fault scarp by Rinehart and Ross (1964). Crack zone trends N40W in tuffaceous material. Rupture extends through pine tree roots. Extension about 50mm, no vertical offset. Cracks discontinuous, and cannot be traced through loose talus slopes to SE.

57. Cracks trending N40W (varying locally to N20W) in tuff. Extensional opening about 90mm, with vertical offset of about 10mm, W side down. Cracks trend across and break tuffaceous rocks. Scree generated during earthquake has obliterated much of the cracking.

58. Cracks trending N20W associated with fault scarp observable on U.S. Forest Service 1972 air photos. Cracks are discontinuous, occur across a dirt road and extend only for about 7.5m on either side of road. Cracking is extensional with about 2mm to 3mm of extension, no vertical displacement.

59. Single crack across road along fault. Discontinuous cracks extend SE upslope beyond road for about 60m. Trend of crack zone N20W. Cracks extend NW for about 15m beyond road.

60. Discontinuous cracks along SW-facing fault scarp. Fault in this location is associated with closed depression and graben. Trend of cracks N45W, extensional opening estimated to be about 20mm - cracks partially obliterated. (Drainage depicted on base map is incorrect. Drainage shown bisecting fault scarp does not flow out of closed depression).

61. No cracks observed along this segment of fault trace. However, forest litter was dense and cracking could have been present.

62. Lurch cracks across road and along

scarp trending N60E. Cracks have extensional opening of 250mm and vertical displacement up to 150mm, NW side down.

Lurch cracks across road that continue along scarp trending N15W, SW side down. West are prominent east-trending slump cracks along margin of valley; observed from helicopter.

Left-stepping extensional cracks across dirt road; strike of crack zone is NW.

Single extensional crack across dirt road about two-thirds the way up older, well-defined E-facing fault scarp. No other cracks seen nearby in natural terrain.

Slump cracks paralleling break in slope between alluvium and hillside nearby (under alluvium?).

Cracks crossing dirt road about normal to road trend. None followed beyond road.

Cracks due to shaking(?) cross dirt road at angles of 90°-60° from the road trend. None could be followed beyond road into natural terrain.

Slump cracks in wet ground with 50mm to 250mm of vertical displacement, down to north. Spring near NW end of cracks apparently increased flow enough to flood gully road at time of earthquakes. Flow had decreased to a trickle on 5/26/80. According to worker on road, spring increased appreciably immediately before and after May 27 M6.0 earthquake.

Fifteen meter wide zone of tension cracks trending N to N15E could only be followed about 30m north of road. Cracks follow road trend from S to S15E for about 30m and then circle to east and end, forming an arcuate trend. Probably related to nearby zone of slumping at 69.

Discontinuous cracking along trend of scarp mapped by Rinehart and Ross (1964). Rinehart and Ross map indicates scarp with

throw down to W, which is incorrect. Throw is down to E, indicated by offset of sandstone beds in exposure south of this location. Cracks trend N05W, no vertical offset. Cracks have partially healed, extensional opening estimated to be about 20mm to 30mm. Cracks extend for only about 45 m to 60m, occur about midway up-slope.

72. Extensional cracks trending N10E. Zone of cracks associated with E-facing slope aligned with two saddles. Extensional opening about 8mm, no vertical offset. Cracks did not extend onto saddle along either end of trace.

73. Extensional cracks trend N30W across dirt road. Cracks can be traced for about 35m to 45m on both sides of road. Extensional opening is about 6mm; no measurable vertical offset.

74. Several sub-parallel, left-stepping cracks with N25W trend cross dirt road. Zone of cracks is 4.5m to 7.5m wide. Extensional opening measures 6mm to 12mm; no vertical offset.

75. Possible slump cracks. Right-stepping set of cracks trend N10W. Extension is about 6mm, no vertical offset. Cracks could not be traced north of Little Antelope Valley Road for more than about 10m.

76. Zone of cracks along base of W-facing fault scarp. Trend of crack zone is N35W. Cracks have extensional opening of about 25mm and vertical offset of about 10mm, down to the W. Cracks can be traced for at least 100m on the road and extend to the SE off the road for about 3m to 6m.

77. Surface rupture along E-facing fault scarp. A graben is formed by this scarp and the W-facing scarp described in 76. Vertical offset along this E-facing scarp is 50mm to 100mm, down to the E. Extensional opening along the cracks is about 50mm. Surface rupture was continuous and generally occurred along the base of the scarp.

78. Isolated cracks trending N20W; no sense of movement measurable.

79. Zone of cracks trending N75W. Cracks probably related to landsliding. Extensional opening estimated to be 5mm to 10mm.

80. Cracks crossing road on Little Antelope Road-Casa Diablo Road seem to be coincident with fault mapped by Bailey and Koeppen (1977). Small discontinuous cracks 3mm wide are visible in cut slope of road. Trend N30W. Unable to trace along trend due to humus.

81. Cracks across Little Antelope Valley Road (gravel road) along general trend of fault mapped by Rinehart and Ross (1964). Trend of cracks about N35W. Cracks partially obliterated, extensional opening estimated to be about 10mm.

82. Minor N-trending cracks in road and adjacent soil at crest of E-facing scarp; 1-2mm of extension (with no offset) in paved road; larger cracks in dirt road to N. Large tension cracks near springs in bentonitic soil, probably partly due to shaking and settlement. Steam issuing from Hot Spring. No fault related cracks in old U.S. Highway 395, but numerous old and new tension cracks in wide zone.

83. N10-20W-trending crack zone on E-facing scarp. Cracks occur in very loose (ashy) soil (partly obscured by recent rain) with 10mm to 20mm of extensional opening, and maximum vertical offset of 50mm to 80mm (down to E). Offset may be enhanced by sliding. Crack zone is 5-10m wide and traced 300m (discontinuously).

84. E-facing scarplet in dirt road on alluvium. Estimated vertical offset of 50mm, down to E. Sinuous crack zone traced N & S of road along margin of meandering slough. Sand boils observed south of road. Offset probably caused by slumping and liquefaction due to shaking.

85. Slump cracks with extension and vertical offset of 50mm, down to E, on individual cracks that rim closed depression.

Cracks probably due to shaking. No cracks seen in loose soil (tephra and colluvial debris) along E-facing scarp of Rinehart and Ross (1964) just west of slump cracks.

86. Slumping immediately south of Union Oil Access Road on Casa Diablo Hot Springs Road (Old Highway 395).

87. Cracks trending N60W on oil tank storage road. Cracks were traceable for 30m to 40m, but have a slightly arcuate trend. No continuity along trend to north. Cracks not visible in meadow to south. Interpreted as slump features.

88. Slump cracks trending N30W. Vertical slickensides in talus.

89. Zone of cracks along scarp trending N30W. Maximum vertical offset 75mm, down to SW, with extension of 50mm. Zone of cracks cuts numerous hydrothermally altered areas. Fumeroles issuing from individual cracks.

90. Subsidence along drain on old Highway 395.

91. Approximate locations of large slump crack zones reported by John Arcularias.

92. Major slump crack zones observed from helicopter, 5/28/80. Locations approximate.

93. SW-facing scarp with extensional cracks (discontinuous) in narrow zone on steepest part of slope. N50W trend. Cracks extend for about 300m. Maximum vertical offset is 20mm to 30mm, SW side down. Extensional opening 20mm to 30mm.

94. NE-facing scarp(s) with discontinuous cracks in zones traceable for about 600m.

95. High NE-facing bedrock scarp with zone of extensive cracking, landsliding and rock falls. Steam issuing from many cracks, including slump crack below scarp. Fumeroles and small pits occur locally. Two or three trees have fallen across scarp as a result of shaking. Pre-existing features

th thermal activity shown by extensive
ay alteration along zone. Maximum off-
t (down to NE) is about 250mm.

. E-facing scarp with cracks along base
scarp. Cracks occur in a narrow zone
0-400m long. Scarp forms margin of
arrow graben with minor cracks occurring
cally on E side (W side down).

. Earthquake fault examined for cracks
om 200m south of Devils Postpile Road
rthward for about 800m. Hairline crack
highway with slight (?) reopening of
d, debris-filled cracks. No cracks
arby in fault fissure to north and south.
roximately 150m north of road, cracks
n be followed to the north along fis-
re (sides or bottom) for 200m to 250m.
acks are open to a maximum of 10mm to
mm with up to 5mm of vertical offset
o variously to E or W). Cracks not
und for next 200m to north. Most of the
acks in the fissure are probably the re-
lt of seismically-induced settlement.
ever, a hairline crack with about 1mm
vertical offset (down to the west) was
ay from the sides of the fissure where
ttlement cracks normally occurred. It
assumed that this hairline crack within
ided alluvium is tectonic.

Slump cracks on toe of landslide.

Surface rupture along a W-facing fault
scarp. Cracks occur about $\frac{1}{4}$ from the top
of the scarp and trend N25-30W. Exten-
sional opening of cracks was about 10mm;
vertical offset. Cracks do not extend
cross Highway 395 along a N25-30W trend.
ever, a single extensional crack per-
pendicular to Highway 395 occurred about
5m east of the fault. The crack in the
inway is in the north-bound lanes and
does not extend into the south-bound
lanes.

Subtle, discontinuous cracks along E-
facing fault scarp. Extensional opening
of cracks is about 12mm; vertical offset is
about 5mm, E side down. Measured displace-
ment is approximate since cracks occur in
relatively cohesionless pumice. Crack

zone trends N10W.

101. Surface rupture about midway up E-
facing fault scarp. Trend of cracks is
N35W. Cracks are discontinuous with
extension of 12mm; no vertical offset.

102. Extensional cracks with N25-30W
trend along E-facing fault scarp. Exten-
sional opening is about 12mm; no vertical
offset. Cracks could be traced for only
about 15m because a thin, clayey crust
preferentially retained the cracks. The
more common, loose pumice did not retain
the cracks.

103. Discontinuous surface rupture along
E-facing fault scarp. Extension on cracks
about 10mm, vertical displacement 10mm to
15mm, down to the east. Width of crack
zone is about 2m (USGS).

104. Discontinuous surface rupture along
SW-facing fault scarp. Zone of cracks
ranges from 2m to 20m wide. Vertical off-
set is 50mm, SW side down. Extensional
opening of cracks ranged from 10mm to
25mm (USGS).

105. Cracks along W-facing fault scarp.
Vertical displacement of 5mm (down to
west) and extensional opening of 5mm
(USGS).

106. Discontinuous surface rupture a-
long subtle, NE-facing fault scarp.
Cracks, which occur in a zone from 1m to
10m wide, are generally extensional with
openings varying from 10mm to 40mm. At
one location 10mm of vertical offset was
observed (USGS).

107. Prominent E-facing fault scarp that
locally forms near vertical scarps. Ex-
tensional cracks, open to 76mm (25mm a-
verage), generally occur along rhyolite
flow-talus contact. Cracks are discon-
tinuous and tend to follow the talus-
bedrock contact rather than the trend of
the fault. No cracking along scarp was
observed away from the prominent rhyolite
outcrops (Refer to figure 1 for this
location).



ROCKFALLS GENERATED BY THE MAMMOTH LAKES EARTHQUAKES OF MAY 25 and 27, 1980

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INTRODUCTION

Rockfalls caused by the May 1980 earthquakes near Mammoth Lakes were a widespread secondary feature of the earthquake sequence. Nine earthquake-related rockfalls occurred, the majority caused by the earthquakes (Sylvester, 1980).

Many landslide features, such as slumping of saturated alluvium, rotational failures, and lateral spreading, were caused by the May 1980 earthquakes. However, this article is limited to the descriptions, in general terms, of the occurrence of rockfalls in selected areas of the Mammoth Lakes region. Field observations of rockfalls were limited because the primary responsibility of the writer was to map surface fault structure. Therefore, various newspaper reports and observations by others have been used when necessary.

ROCKFALL DESCRIPTIONS

Landslide nomenclature can be complex, sometimes confusing, depending on the reference used. The following definitions from the American Geological Institute's Glossary of Geology will apply to this article: rockfall is defined as the relatively free falling or precipitous movement of a newly detached segment of rock of any size from a cliff or other steep slope; movement may be straight down the slope; it is not guided by an underlying slip surface; rock avalanche is defined as the very rapid downslope movement of rock fragments, typically the result of large rockfalls; characteristic features include chaotic distribution of

large blocks, flow morphology and internal structure, relative thinness in comparison to large areal extent, high porosity, angularity of fragments, and lobate form.

Convict Lake

Convict Lake campground, located on the northeast side of the lake, was closed after the first M 6.0 earthquake on May 25 due to the hazard of rockfalls and



Photo 1. Large boulder that rolled down a southeast-facing slope in McGee Creek canyon and finally stopped in the middle of a corral. View is to southeast. Corral is located in SE $\frac{1}{4}$ of section 32, T4S, R29E. Photo by C. R. Real.

rock avalanches (Sylvester, 1980). Rock avalanches overran snowfields and talus slopes at the south and west end of Convict Lake where precipitous slopes bound the lake (R. McJunkin, p.c.). The Convict Lake area was subject to frequent rockfalls caused by the many aftershocks of the earthquake sequence. Dust clouds generated by rockfalls were a common sight over Convict Lake after the initial May 25 events.

McGee Creek

Dislodged boulders barely missed structures in McGee Creek in two separate instances. A large, flat boulder (3m x 3m x 1m) passed within a few meters of a pack station about 1.5km southwest of the intersection of the Hilton Creek fault and McGee Creek Road, leaving a path of broken trees down the steep northwest slope of McGee Mtn. A large boulder came to rest in a corral about 80m northeast of the pack station after breaking through the northwestern fence (photo 1). Many rock avalanches occurred along the steep slopes of McGee Creek (see frontispiece). An abundance of smaller rocks were shaken loose and rolled down the east-facing scarp of the Hilton Creek fault in the McGee Creek area.

Canyon Northwest of Mammoth School

A large rhyolite boulder (about 7.6m x 6m x 4.5m) bounced down the slope of a southwest-facing fault scarp located about 1.5km northwest of the Mammoth Elementary School (photos 2a, 2b). Impact craters averaging 1m deep defined the boulder's path down a talus slope; one large impact crater was about 2.2 to 2.4m deep. Rockfalls were common along this southwest-facing fault scarp (see Taylor and Bryant, accompanying article, Plate 1, sections 21, 27, 28, T 3 S, R 28 E).

Devils Postpile

Three basalt columns in the Devils Postpile National Monument, located 11km west of Mammoth Lakes, were toppled during the May 1980 earthquakes. Two additional

columns, weakened by the May 1980 earthquakes, fell on August 8, 1980 (Robert Bartlett, San Francisco Chronicle, August 26, 1980).

GEOLOGIC HAZARD OF ROCKFALLS

Rockfalls associated with earthquake shaking are a recurring hazard in the Sierra Nevada. The potential for rockfalls exists in any area where blocky, jointed outcrops occur along slopes. In the Mammoth Lakes area, slate, hornfels, and sandstone of the Mt. Morrison roof pendant seemed to be more susceptible to rockfalls than granitic rocks during the May 1980 earthquakes, probably because most of the metamorphic rocks are intensely fractured and jointed, producing loose slabby blocks. Earthquake-related rockfalls and rock avalanches near Convict Lake, which is bounded on the north, west, and south by steep slopes of slate, hornfels, and sandstone (Rinehart and Ross, 1964), illustrate this occurrence. In addition, rock avalanches on the near-vertical slopes of Laurel Mountain, Bloody Mountain, and Mt. Morrison were observed during helicopter overflights on May 28, 1980.

Rockfalls of various sizes almost always were associated with fault scarps along which surface rupture associated with the May 1980 earthquakes occurred (Taylor and Bryant, accompanying article Plate 1, localities 4, 8, 55, 56, 71, 95). In the higher, more rugged country west and south of Mammoth Lakes, rockfalls and rock avalanches were widespread. Many back country roads and trails were closed due to rockfalls after the first M 6.0 earthquake on May 25. After the unusual large snowpack had melted, evidence of additional rockfalls in the Mammoth Lake region was noticed by U.S. Forest Service personnel (Bartlett, San Francisco Chronicle, August 26, 1980).

ROCKFALLS IN YOSEMITE VALLEY

Rockfalls generated by the May 1980 earthquakes occurred in Yosemite Valley located about 70km west of Mammoth Lake.

Two hikers in Yosemite Valley were severely injured by a rockfall. The occurrence of rockfalls in Yosemite is common, and evidence indicates that many of the talus cones on the valley floor were generated during large earthquakes.

A first-hand account of this geologic process is given in John Muir's book *The Yosemite* (Doubleday & Company, Inc., 1962). Muir had long thought that some talus slopes in Yosemite Valley were formed by an earthquake that occurred about 300 to 500 years ago. Muir's theory was confirmed in the morning of March 26, 1872, when a 6.8+ earthquake shook the Sierra Nevada. The following excerpts document rockfalls in Yosemite Valley generated by the 1872 Owens Valley earthquake:

"The avalanche taluses, leaning against the walls at intervals of a mile or two, are among the most striking and interesting of the secondary features of the [Yosemite] Valley. They are from about three to five hundred feet high, made up of huge, angular, well-preserved,

unshifting boulders, and instead of being slowly weathered from the cliffs like ordinary taluses, they were all formed suddenly and simultaneously by a great earthquake that occurred at least three centuries ago...

"...I was long in doubt on some points concerning the origin of these taluses. Plainly enough they were derived from the cliffs above them, because they are of the size of scars on the wall, the rough angular surface of which contrasts with the rounded, glaciated, unfractured parts. It was plain, too, that instead of being made up of material slowly and gradually weathered from the cliffs like ordinary taluses, almost every one of them had been formed suddenly in a single avalanche, and had not been increased in size during the last three or four centuries, for trees three or four hundred years old are growing on them, some standing at



Photo 2a. View northeast across unnamed canyon northwest of Mammoth Elementary School. Path of large rhyolite boulder that was dislodged from near the top of the slope is defined as a series of impact craters down the talus slope. See photo 2b for size of boulder. Photo by W. A. Bryant.



Photo 2b. Close-up of large rhyolite boulder in photo 2a; view southwest. Note person standing in front of boulder for scale. Smaller rocks to right of boulder also fell during May 1980 earthquakes. Other large boulders lying in this northwest-trending canyon are rockfalls that were probably generated as the result of earlier earthquakes. Photo by C. R. Real.

the top close to the wall without a bruise or broken branch, showing that scarcely a single boulder had ever fallen among them. Furthermore, all these taluses throughout the range seemed by the trees and lichens growing on them to be of the same age. All the phenomena thus pointed straight to a grand ancient earthquake. But for years I left the question open, and went on from canyon to canyon, observing again and again; measuring the heights of taluses throughout the range on both flanks, and the variations in the angles of their surface slopes; studying the way their boulders had been assorted and related and brought to rest, and their correspondence in size with the cleavage joints of the cliffs from whence they were derived, cautious about making up my mind. But at last all doubt as to their formation vanished.

"At half-past two o'clock of a moonlit morning in March, I was awakened by a tremendous earthquake, and though I had never before enjoyed a storm of this sort, the strange thrilling motion could not be mistaken, and I ran out of my cabin, both glad and frightened, shouting, 'A noble earthquake! A noble earthquake!' feeling sure I was going to learn something. The shocks were so violent and varied, and succeeded one another so closely, that I had to balance myself carefully in walking as if on the deck of a ship among waves, and it seemed impossible that the high cliffs of the Valley could escape being shattered. In particular, I feared that the sheer-fronted Sentinel Rock, towering above my cabin, would be shaken down, and I took shelter back of a large yellow pine, hoping that it might protect me from at least the smaller outbounding boulders. For a minute or two the shocks became more and more violent--flashing horizontal thrusts mixed with a few twists and battering,

explosive, upheaving jolts,--as if Nature were wrecking her Yosemite temple, and getting ready to build a still better one.

"I was now convinced before a single boulder had fallen that earthquakes were the talus-makers and positive proof soon came. It was a calm moonlight night, and no sound was heard for the first minute or so, save low, muffled, underground, bubbling rumblings, and the whispering and rustling of the agitated trees, as if Nature were holding her breath. Then, suddenly, out of the strange silence and strange motion there came a tremendous roar. The Eagle Rock on the south wall, about a half a mile up the Valley, gave way and I saw it falling in thousands of the great boulders I had so long been studying, pouring to the Valley floor in a free curve luminous from friction, making a terribly sublime spectacle--an arc of glowing, passionate fire, fifteen hundred feet span, as true in form and as serene in beauty as a rainbow in the midst of the stupendous, roaring rock-storm. The sound was so tremendously deep and broad and earnest, the whole earth like a living creature seemed to have at last found a voice and to be calling to her sister planets. In trying to tell something of the size of this awful sound it seems to me that if all the thunder of all the storms I had ever heard were condensed into one roar it would not equal this rock-roar at the birth of a mountain talus.

"The first severe shocks were so over, and eager to examine the new-born talus I ran up the Valley in the moonlight and climbed upon it before the huge blocks, after their fiery flight, had come to complete rest. They were slowly settling into their places, chafing, grating against one another, groaning, and whispering; but no motion was visible ex-

cept in a stream of small fragments pattering down the face of the cliff. A cloud of dust particles, lighted by the moon, floated out across the whole breadth of the Valley, forming a ceiling that lasted until after sunrise, and the air was filled with the odor of crushed Douglas spruces from a grove that had been mowed down and mashed like weeds...

"...It was long before the Valley found perfect rest. The rocks trembled more or less every day for over two months, and I kept a bucket of water on my table to learn what I could of the movements. The blunt thunder in the depths of the mountains was usually followed by sudden jarring, horizontal thrusts from the northward, often succeeded by twisting, upjolting movements...

"...Judging by its effects, this Yosemite, or Inyo earthquake, as it is sometimes called, was gentle as compared with the one that gave rise to the grand talus system of the range and did so much for the canyon scenery. Nature, usually so deliberate in her operations, then created, as we have seen, a new set of features, simply by giving the mountains a shake--changing not only the high peaks and cliffs, but the streams."

CONCLUSION

The danger of rockfalls in the Sierra Nevada is a persistent and obvious geologic hazard. Rockfalls can occur at anytime in mountainous terrain, but, as observed by Muir, they are very common during earthquakes. The combination of steep slopes, blocky, jointed outcrops, and earthquake shaking can produce swift-moving boulders and rock avalanches that have a high potential for causing property damage and injury or death. Earthquakes during the winter and early spring months may produce rock avalanches lubricated with snow and ice that can become

extremely fast-moving, destructive hazards.

Awareness of rockfall hazards should be a part of geologic investigations for the planning and siting of public utilities, public facilities, campgrounds, and other recreational facilities in mountainous, earthquake-prone areas. It is important when conducting such studies that the investigation be extended offsite. This is necessary because, although a site may be on flat ground away from steep slopes, swift-moving rockfalls or rock avalanches can extend out onto flat surfaces for a considerable distance. The danger of rockfalls, obvious near steep slopes, may also be present on an otherwise safe-appearing site.

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STRONG-MOTION INSTRUMENTATION PROGRAM RESULTS FROM
THE MAY, 1980, MAMMOTH LAKES, CALIFORNIA EARTHQUAKE SEQUENCE

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INTRODUCTION

Fourteen (14) accelerograph stations, instrumented by the California Division of Mines and Geology's Strong-Motion Instrumentation Program (CDMG-SMIP), were triggered by one or more of the Mammoth Lakes earthquakes occurring between 25-28 May, 1980. A total of 1,082 data traces were recorded from 46 earthquakes beginning with the $M_L = 6.5$ (CIT), [$M_L = 6.0$, UCB] event at 1633 hours (UTC) on 25 May through the $M_L = 4.8$ (CIT) event at 0700 hours (UTC) on 28 May 1980 (all magnitudes cited herein are preliminary values from the California Institute of Technology, Seismological Laboratory and, where available, from the University of California - Berkeley, in brackets).

Preliminary scaling of the uncorrected accelerograms indicate 347 of the data traces to have recorded significant (≥ 0.05 g, ground motion; ≥ 0.10 "g", structural response) peak accelerations. Of these, the largest ground and structural peak accelerations were 0.49 g and > 1.00 g respectively; these values were recorded at Convict Creek and Mammoth Lakes High School.

STRONG MOTION STATIONS AND DATA

The SMIP stations which were triggered during the 25-28 May 1980 time span are shown in Figure 1; correlation of events at recording stations are listed in Table 1. In Table 2 is an alphabetical listing of the stations, their geographic coordinates, instrument locations, type of

station (i.e., free-field or structure) and the number of events recorded at that station. A selected listing of significant earthquake induced ground and/or structural motion is given in Table 3 for events of $M_L \geq 6.0$. The largest values of peak accelerations were recorded at the Convict Creek, Long Valley Dam, and Mammoth Lakes High School stations during the events of $M_L \geq 6$; Figure 2 shows the spatial distribution of these stations relative to these epicenters. A general station description and recording history of these three stations, located within 15 kilometers of the $M_L \geq 6$ epicenters, is presented:

Convict Creek

This station was first instrumented with a tri-axial strong motion accelerograph (SMA-1, no radio) on March 1974. The instrument is housed in a single story, corrugated steel storage building and is bolted to the PC concrete slab floor. The instrument's accelerometer axes are oriented 1 (L) = 180° , 2(V) = Up, 3 (T) = 90° , azimuthal, such that the instrument's case motion-direction causes an upward trace deflection on accelerograms. The station is located at Sierra Nevada Aquatic Research Laboratory, three miles west of Crowley Lake on the south bank of Convict Creek. On 16 August 1979, instrumentation was changed to a SMA-1T to provide WWVB radio time on the accelerograms. Significant peak accelerations recorded at this site prior to 25 May 1980 are:

<u>Event</u>	<u>Peak Acceleration (g)</u>	24 January 1979	0.07, horizontal (360° azimuthal), center crest
24 January 1979	0.10, horizontal (90° azimuthal)		
16 June 1979	0.08, horizontal (180° azimuthal)		
6 December 1979	0.05, horizontal (90° azimuthal)		
8 December 1979	0.06, horizontal (180° azimuthal)		

This free-field accelerograph station recorded all earthquakes of $M_L \geq 5$ during this most recent Mammoth Lakes earthquake sequence, and many of the lesser magnitude events. A total of 37 distinct earthquakes were recorded at this site. The largest accelerations were 0.49 g & 0.43 g, horizontal and vertical motion, respectively.

Long Valley Dam

The Long Valley Dam is an earthfill dam owned and operated by the Los Angeles Department of Water and Power. This structure was initially instrumented by SMIP in November, 1975, with three SMA-1s. An SMA-1T (WWVB radio equipped) was located on the north (left) abutment, an SMA-1 on the left crest, and another SMA-1 on the right crest of the dam; these three instruments were interconnected to provide a common time base. The instruments were oriented with the horizontal axes at 1 (L) = 360°, 3 (T) = 270° azimuthal.

Significant peak acceleration values recorded at the Long Valley Dam SMIP instruments prior to 25 May 1980 are:

<u>Event</u>	<u>Peak Acceleration (g)</u>
4 October 1978 (1643 hours)	0.26, horizontal (360° azimuthal), abutment
aftershock (1739 hours)	0.18, horizontal (360° azimuthal), abutment

During August 1979, a central recording accelerograph (CRA-1) with 13 data channels was added to the station instrumentation scheme, augmenting the three existing 3 SMA-1 positions. All instruments were interconnected for common triggering and WWVB radio time. Three of the CRA-1's forced-balance accelerometers (FBAs) were installed in an orthogonal configuration on a small (32 inch square, 4 inch thick) PC concrete slab. The instruments were located adjacent to the left (also called the center) crest SMA-1 which is housed in a small, corrugated steel, instrument housing on a 5 foot square, approximately 2 feet thick concrete slab. The SMA's axes were realigned to 1 (L) = 90°; 3 (T) = 30° azimuthal. The CRA-1's accelerometers are oriented parallel to the SMA such that:

<u>CRA-1 trace no.</u>	<u>parallels SMA trace</u>
6	1 (L)
7	2 (V)
8	3 (T)

A total of 21 earthquakes were recorded by one or more of the Long Valley accelerographs between 25 May and 28 May 1980. Thirteen events generated significant peak accelerations, the highest of which was 0.52 g recorded on the CRA-1's trace no. 6 (corresponding to the SMA-1 at the center crest of the dam) during the $M_L = 6.3$ event on 27 May. The corresponding accelerometer in the SMA-1 at this location responded to the input-motion with a value of 0.47 g acceleration, in an orientation of 90° azimuthal. While these accelerations represent the highest values recorded at this station's structural response, a higher acceleration was recorded by the left abutment instrument - a single

frequency spike of 0.99 g, 5.4 seconds after triggering (Turpen, 1980).

This site provided an approximate comparison test for different type instruments in the measurement of dynamic structural response during strong motion input. Preliminary examination of accelerograms recovered from the May 1980 events shows less than a 1% g difference between the corresponding peak accelerations for all but one event. An example of this test site's response is shown in figure 3. Variation over time is apparently caused by a slight difference in film transport speed through the different accelerograph cameras (CRA-1 and A-1).

Mammoth Lakes High School Gymnasium

A 10 channel, CRA-1 accelerograph system was installed at this station in February 1977. The building is a rectangular, single story gymnasium with steel trusses and columns, a horizontal steel bracing system in the plane of the lower truss chord; vertical steel bracing casings in cast-in-place PC concrete shear walls. The building's foundation type is reinforced PC concrete spread footings. Information from the CDMG-SMIP station (see, Sacramento).

The building is instrumented such that it measures one through four record foundation (ground) motion, and traces five through six record structural response. The system was triggered by a VS-1 vertical starter calibrated to .01 g activation, 10 second run time. On 19 September, 1979, the VS-1 was modified to provide a 60 second run time and recalibrated to measure long period movement of structural response.

On 15 May 1980, the installation was modified to include a horizontal starter, model HS-0, calibrated to .01 g activation, and was mounted on a lower truss chord.

Significant peak accelerations, ground and structure, generated by events prior to 25 May 1980 are:

<u>Event</u>	<u>Peak Acceleration (g)</u>
4 October 1978	0.09, horizontal (344° azimuthal), ground motion
	0.34, horizontal (344° azimuthal), roof truss (trace 8)
aftershock	Less than 0.05, ground motion
	0.11, horizontal (344° azimuthal), roof truss (trace 8)

The Mammoth Lakes High School station recorded 46 earthquakes. Beginning with the 25 May 1633 hours (UTC) event, the accelerograph was triggered and ran continuously for 11 minutes. The recording system at this station was triggered by both a vertical starter (VS-1) calibrated to 0.005 g sensitivity and a horizontal one (HS-0) calibrated to 0.01 g sensitivity. The accelerogram, generated during the 11 minutes, shows P and S wave motion occurring every 15-20 seconds during the entire run. Over the next 72 hours, this accelerograph was triggered and recorded a total of over 61 minutes of ground motion and structural response. Significant ground motion peak accelerations were generated and recorded for 7 events (Table 1).

A total of 46 earthquakes (with acceleration amplitudes great enough to trigger the system), occurring between 1633 hours (UTC) on 25 May and 0517 hours (UTC) on 28 May, 1980, were recorded at this station. Because this site does not have WWVB radio time, identification of the recorded events is subjective in nature, based on bracket dates and times when the station was serviced by SMIP technicians.

OTHER DATA

Significant accelerograms were generated at CDMG-SMIP free-field stations located at distances greater than 20 km from epicenters; those stations are Benton, Bishop, Fresno, Miramonte, Mono Lake, and Paradise Lodge. Of these, only the Benton, Bishop, and Mono Lake accelerograms can be identified with specific earthquake date and time of occurrence (Turpen, 1980). The data generated by these events suggests a non-uniform attenuation of accelerations with increasing epicentral distances over "far-field" ($\sim > 20$ km). This effect was also observed in SMIP accelerograms generated at other stations during California earthquakes at Santa Barbara, 1978, Coyote Lake, 1979, and the Imperial Valley, 1979 (Porter, 1978; Porcella and Matthiesen, 1979; McJunkin and Ragsdale, 1980). The plethora of accelerograms, generated by the May, 1980, Mammoth Lakes earthquake sequence, offers a unique set of data which will be of considerable interest to investigators studying the attenuation of peak acceleration in the near-field under conditions of varying distances and soil/rock ratios.

Engineers and seismologists have conducted many studies dealing with the attenuation of peak accelerations (Trifunac, 1976; Seed et al., 1976). The influence of attenuation on peak acceleration in the near-field has been extrapolated from accelerograms of events at distances greater than 20 km based on statistical regression analysis techniques (Trifunac, 1976; Seed et al., 1976). The accelerograms from the SMIP stations will be of value in near-field studies due to their proximity to multiple epicenters of earthquakes with varying depths (2.2- 21.0 km) and magnitudes (four with $M_L \geq 6$; four with $M_L = 5.0$ to 5.9; and 58 with $M_L = 4.0$ to 4.9).

SUMMARY

CDMG-SMIP accelerograms, which, by preliminary scaling, indicate a recording of significant peak acceleration generated during the May 1980 Mammoth Lakes earthquake sequence, are being reviewed by SMIP management. Digitizable ones will be selected for data processing and analysis. When this processing is completed, relative velocities, displacements, Fourier response spectra and other related data will be made available to the user community.

Peak accelerations cited in this paper were scaled from reproduced copies of the uncorrected accelerograms. The values are preliminary and subject to revision pending a more detailed examination.

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TABLE 1

A chronological (PST) listing of earthquakes recorded at CDMG-SMIP strong motion stations is shown below; station identification numbers are tabulated along with local magnitude reported by CIT and UCB (shown in brackets).

Date/Time	M_L	SMIP Station Numbers
25th/0933	6.5 [6.1]	0*,10,45,46,98*,100*,101,171,214*,298,301*,361
0936	5.0	99*,214*,301*
0940	4.0	99
0942	4.2	99*,301
0945	4.0	301
0949	6.0 [6.0]	98,99*,100,214*,301*
0952	4.6	99,214
0956	4.2	99
1006	4.9 [4.6]	99
1008	4.6 [4.7]	99,214
1017	3.9	99*
1049	4.6 [4.6]	99,214
1241	4.5	99
1245	6.7 [6.1]	0*,10,45,46,98,99*,100*,101,171,214*,298,361
1255	3.9	99
1323	4.7	99*
1336	5.5 [5.7]	99*,214*
1339	4.3	99*,214*
1345	3.6	99*
1359	4.9 [5.0]	99*,214
1511	4.1	214
1757	4.4	214
1819	4.7 [4.6]	214,301*
2025	3.6	99
2049	4.0	214*
2137	4.0	99*
2257	4.6 [4.7]	99

TABLE 1 (cont.)

Date/Time	M_L	SMIP Station Numbers
26th/0321	4.1 [4.5]	99*,214*
0340	3.8	99
0404	4.0	99,214*
0524	5.2 [5.1]	99*,214*,301*
0604	4.1	214
0657	3.8	99
0920	4.5 [4.8]	99
1130	(+)	99
1158	4.9 [5.7]	99,214*,301*
1304	3.8	99
27th/0751	6.3 [6.2]	Ø*,10,45,46,72,98,99*,100*,101,171*,214*,298,361
0911	3.8	99
1201	5.0 [4.8]	99,214*
1658	3.8	99
2103	3.8	99
2216	4.8 [4.9]	99,301*

*denotes significant (> 0.05 g) peak accelerations.

(+) magnitude not determined.

Note: Earthquake dates and times listed in this table have been converted from WWVB radio time code received by the recording instruments. The following conversion formulas are provided for those persons accustomed to using WWVB time codes:

Calendar date	25 May 1980	=	Julian date	146
	26 May 1980	=		147
	27 May 1980	=		148

Pacific Daylight Time = Universal Time Coordinated minus (-) 7 hours,
(PDT) (UTC)

Time of events listed in Table 1 is rounded to the nearest minute from station trigger time in hours and minutes in accordance with a 24 hour clock system.

TABLE 2

Alphabetical listing of CDMG strong-motion accelerograph stations that triggered and recorded one or more events of the May 1980 Mammoth Lakes earthquake sequence.

No.	Station Name	Coordinates	No. events Recorded	Structure Type/Size	Instrument Location(s)
100	Benton	37.818°N 118.475°W	4	1-story building	ground level
171	Bishop	37.370°N 118.395°W	3	2-story cement bk building	ground level
45	Centerville	36.734°N 119.486°W	3	1-story building	ground level
99	Convict Creek	37.614°N 118.831°W	37	1-story building	ground level
10	Fresno (State University)	36.813°N 119.748°W	3	seismic vault	basement level
298	Independence (L.A. Water & Power Bldg.)	36.800°N 118.199°W	3	1-story concrete building	ground level & roof
46	King's Cyn. Nat'l Park (Cedar Grove)	36.787°N 118.675°W	3	T-hut	Gr
214	Long Valley Dam	37.588°N 118.705°W	17	earth dam	abutment L & R crest
301	Mammoth Lakes (High School Gym.)	37.641°N 118.963°W	47	2-story building	ground level roof
72	Miramonte (Conservation Camp)	36.641°N 119.050°W	1	1-story building	ground level
98	Mono Lake	37.940°N 119.065°W	4	Armco building	ground level
361	Tinnemaha Dam	37.055°N 118.239°W	3	earth day	abutment L & C crest
101	Tinnemaha (CIT Seismic Vault)	37.055°N 118.239°W	3	seismic vault	ground level
Temporary Station :					
Ø	Paradise Lodge	37.481°N 118.602°W	3	1-story building	ground level

TABLE 3

Partial listing of earthquake ground motion and other pertinent data for CDMG accelerograph stations triggered by the Mammoth Lakes 25-27 May 1980 earthquake sequence. Stations are arranged in order of increasing distance from epicenter(s). Epicenters for events are coded by local date and time.

No.	Station Name	Coordinates	Date	Time	M _L (CIT)	Epicentral ¹ Distance	Acceleration Azimuth ² Max(g)	Ground/ Structure
99	Convict Creek	37.818°N 118.475°W	25th	0933	6.5	1.5 [69°]	180° Up 90°	0.46 0.43 0.43
			25th	0949	6.0	8.7 [100°]	180° Up 90°	" " "
			25th	1245	6.7	6.1 [4°]	180° Up 90°	" " "
			27th	0751	6.3	11.9 [353°]	180° Up 90°	" " "
301	Mammoth Lakes (High School Gym.)	37.641°N 118.963°W	25th	0933	6.5	10.8 [289°]	254° Up 344° 254°	0.33 0.26 0.26 1.07
			25th	0949	6.0	3.5 [296°]	254° Up 344° 254° 344°	0.37 0.27 0.43 >1.00 >1.00
								ground " " roof beam ground " " roof beam "

TABLE 3 (cont.)

214	Long Valley Dam	37.588°N 118.705°W	25th	0933	6.5	12.7 [101°]	90° Up 360°	0.28 0.13 0.42	left abutment " "
							90° Up 360°	0.23 0.15 0.42	left crest " "
							90° Up 360°	0.15 0.14 0.20	right crest " "
							90° Up 360°	0.07 0.07 0.11	downstream (bedrock) "
			25th	0949	6.0	20.1 [103°]	90° Up 360°	0.07 0.04 0.19	left abutment " "
							90° Up 360°	0.04 0.05 0.06	left crest " "
							90° Up 360°	0.04 0.04 0.05	right crest " "
							90° Up 360°	0.01 0.02 0.04	downstream (bedrock) "
			25th	1245	6.7	11.9 [75°]	90° Up 360°	0.19 0.12 0.49	left abutment " "

TABLE 3 (cont.)

Long Valley Dam (cont.)

													90°	0.12	left crest
													Up	0.14	"
													360°	0.24	"
													90°	0.06	downstream
													Up	0.07	(bedrock)
													360°	0.11	"
27th	0751	6.3	14.1	[50°]									90°	0.41	left abutment
													Up	0.32	"
													360°	0.99	"
													90°	0.52	left crest
													Up	0.21	"
													360°	0.30	"
													90°	0.49	right crest
													Up	0.24	"
													360°	0.47	"
													90°	0.17	downstream
													Up	0.09	"
													360°	0.24	"
Ø	Paradise Lodge	37.481°N 118.602°W	27th	0751	6.3	20.6							150°	0.12	ground
													Up	0.09	"
													60°	0.09	"
98	Mono Lake	37.940°N 119.065°W	25th	0933	6.5	39.8							85°	0.06	ground
													Up	0.04	"
													355°	0.08	"
171	Bishop	37.370°N 118.395°W	27th	0751	6.3	41.6							270°	0.04	ground
													Up	0.02	"
													180°	0.08	"

TABLE 3 (cont.)

100	Benton	37.818°N 118.475°W	27th	0751	6.3	46.8	360° Up 270°	0.18 0.07 0.11	ground " "
101 361	Tinemaha (Dam) " (Seismic Vault)	37.055°N 118.239°W	27th	0751	6.3	72.7	less than 0.05 all traces		
46	King's Canyon Nat'l Park (Cedar Grove)	36.787°N 118.675°W	27th	0751	6.3	81.1	less than 0.05 all traces		
298	Independence (L.A. Water & Power Bldg.)	36.800°N 118.199°W	27th	0751	6.3	96.5	less than 0.05 all traces		
45	Centerville	36.734°N 119.486°W	27th	0751	6.3	101.2	less than 0.05 all traces		
10	Fresno (State University)	36.813°N 119.748°W	27th	0751	6.3	112.0	less than 0.05 all traces		
72	Miramonte	36.406°N 119.050°W	27th	0751	6.3	123.7	less than 0.05 all traces		

¹ Distance from epicenters, in kilometers; and in brackets, azimuthal direction from epicenter to SMIP station for earthquakes' coordinates (as determined by CDMG- Cramer and Toppozada, 1980).

M _L	Date	Origin Time		Latitude	Longitude	Depth
		h	m			
6.5	25th	09	33	37.609°N	118.847°W	8.85km
6.0	25th	09	49	37.627°N	118.927°W	13.79km
6.7	25th	12	44	37.559°N	118.835°W	15.93km

TABLE 3 (cont.)

6.3	27th	07	50	57.17	37.506°N	118.826°W	14.15km
-----	------	----	----	-------	----------	-----------	---------

Distances for stations farther than 50 km from epicenters were calculated using formulae developed by C.F. Richter (Richter, 1943).

²Azimuthal direction of ground acceleration for upward trace deflection on accelerogram (degrees, clockwise from North).
Max(g) is the decimal fraction of acceleration due to gravity; nominal value of one "g" $\approx 9.8 \text{ m/sec}^2$.
Time of events listed in Table 3 is rounded to the nearest minute from station trigger time in hours and minutes in accordance with a 24 hour clock system.

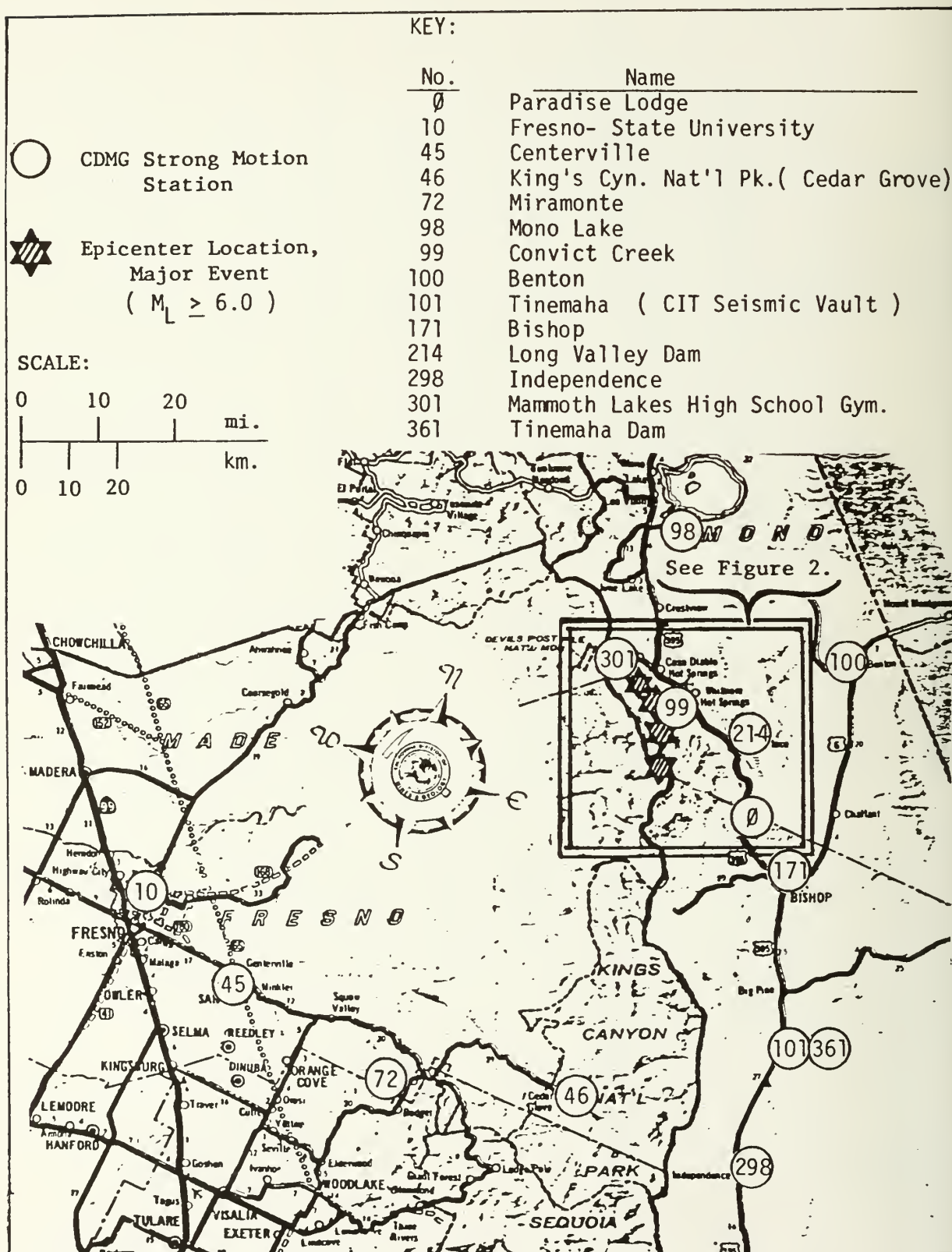


Figure 1. CDMG Strong-Motion Stations triggered during the May 1980 Mammoth Lakes earthquake sequence by one, or more of the $M_L \geq 6.0$ events.

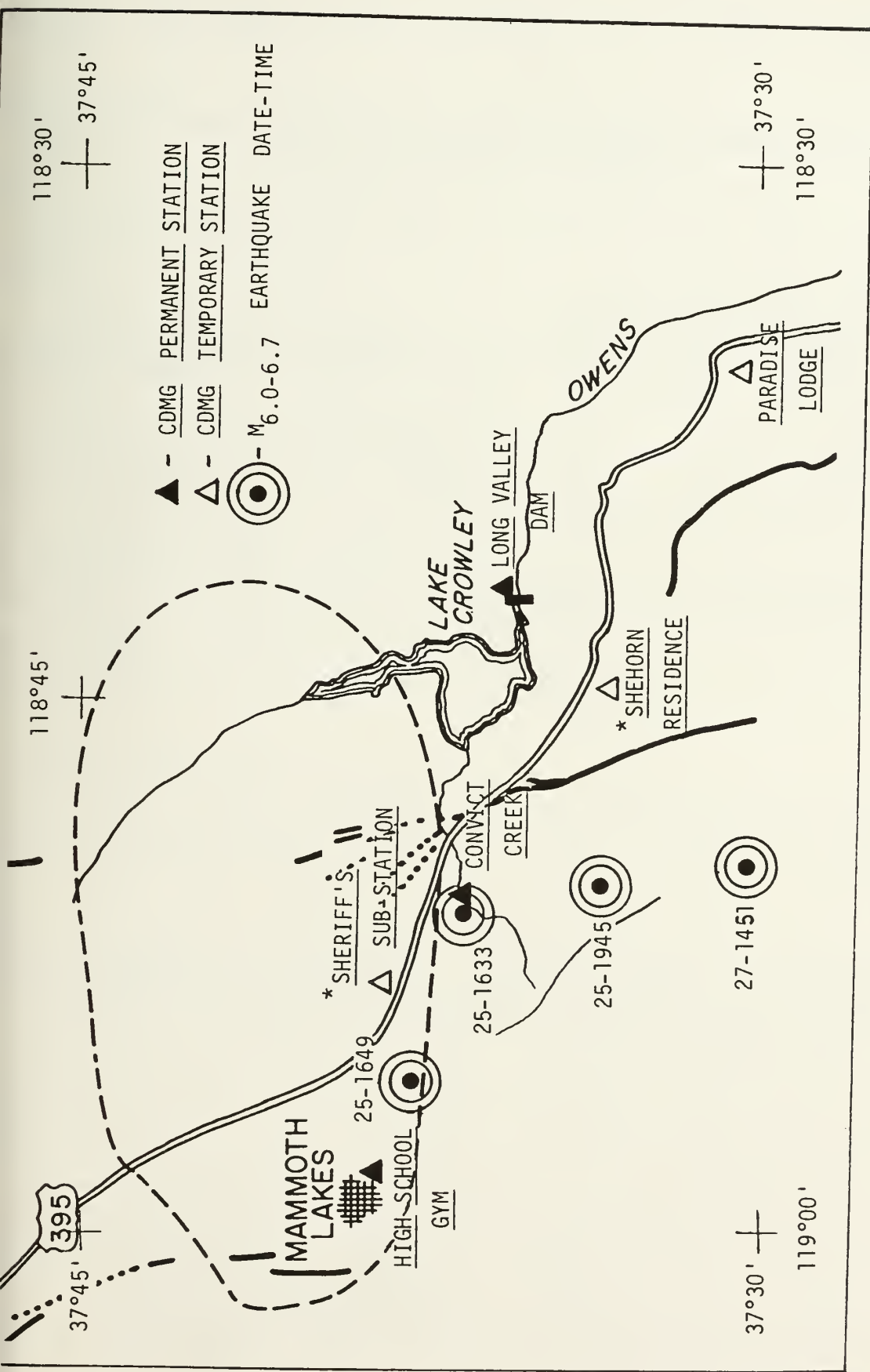


Figure 2. Location of CDMG Strong-Motion Stations relative to the May 1980, Mammoth Lakes major earthquake epicenters. The CDMG permanent stations recorded the most significant peak accelerations of the earthquake sequence.

* CDMG Temporary stations installed and operational after 27 May 1980.

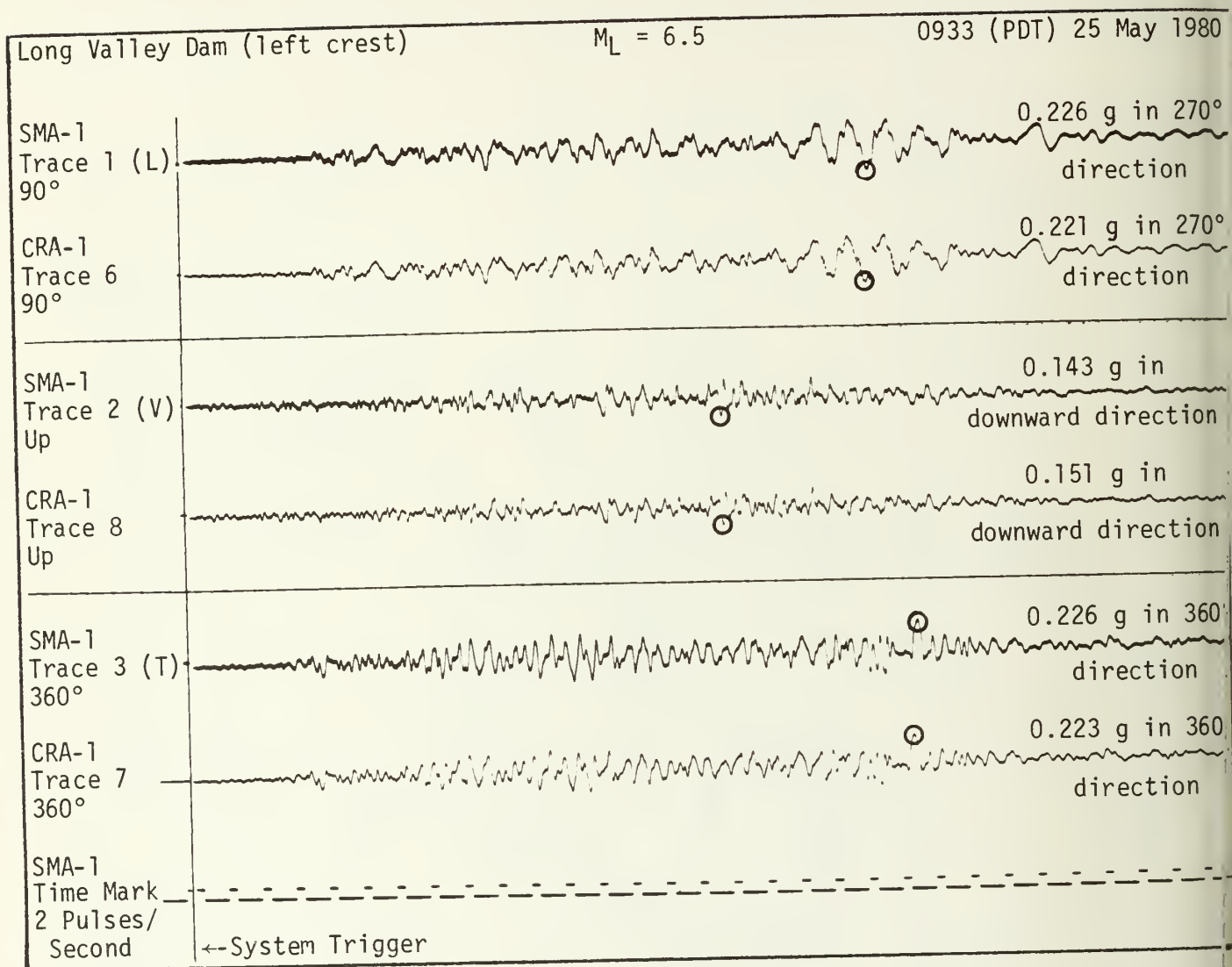


Figure 3.

Comparison of paralleled instrument response to strong motion generated during the $M_L = 6.5$ earthquake of 0933 hours, 25 May 1980 at the Long Valley Dam station. The slight time variance between instrument traces may be attributed to differing camera motor's film drive speeds.

A SEISMOLOGICAL STUDY OF THE MAY, 1980, AND EARLIER EARTHQUAKE ACTIVITY NEAR MAMMOTH LAKES, CALIFORNIA

By

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ABSTRACT

On May 25, 1980, a sequence of M6 earthquakes culminated a year of M4 earthquake swarms near Mammoth Lakes, California. Local CDMG seismograph and accelerograph coverage, in addition to existing regional seismographs, provides a detailed picture of this activity. Historically, the seismicity of the Long Valley to Bishop portion of the Eastern front of the Sierra Nevada (EFSN) has been high, with $M \geq 5.5$ earthquakes occurring every ten to twenty years. The May 1980, 5 earthquakes represent the greatest seismic activity along the EFSN during the present century.

A detailed examination of the $M \geq 4$ earthquakes of the series shows that the "fore-swarms" migrated eastward and southward along the southern boundary of the Long Valley caldera between September, 1979, and May, 1980. On May 25, 1980, a complex migration of $M \geq 5$ earthquakes began from E to W, again along the southern boundary of the caldera. The first M6 occurred to the east near Convict Lake followed 16 minutes later by a second M6, 8 km to the west near Casa Diablo. Then the seismicity migrated southward. The third M6 occurred three hours later 5 km south of the first M6, and the fourth M6 occurred on May 27, 5 km south of the third M6. All four M6 events and most of the aftershocks occurred west of the Hilton Creek fault which had only minor activity associated with it. The $M \geq 3.5$ aftershocks, recorded by a nine station CDMG local seismograph network, indicate a complex aftershock zone west of the Hilton Creek fault and along and south of the caldera boundary.

Focal mechanisms for the four M6 earthquakes, as well as for the "fore-swarms", are strike-slip with E-W and N-S nodal planes. The sense of motion is right-lateral on E-W faults and left-lateral on N-S faults. Comparison with focal mechanisms for microearthquakes, recorded in the early 1970's, suggests temporal and some spatial rotation in the regional stress field from ENE-WSW to NE-SW.

b-values for the Mammoth Lakes activity are 0.9. This is a typical value for California and suggests a tectonic rather than a volcanic origin for these earthquakes.

INTRODUCTION

Beginning on May 25, 1980, a series of M6 earthquakes occurred in the Mammoth Lakes- Lake Crowley area. Over the previous year, the occurrence of several swarms of M4 earthquakes along the southern boundary of the Long Valley caldera had prompted the California Division of Mines and Geology (CDMG) to instrument the area with sensitive seismographs. Four CDMG strong-motion accelerographs were also operational in the area prior to this activity providing additional data for the larger events. The region south of Lake Crowley had been shaken by a M5.8 (BRK, CIT) earthquake and its aftershock sequence in October, 1978.

This report presents preliminary seismological results from CDMG's earthquake monitoring activities in the Mammoth Lakes area for the May 25 earthquake series. Results of studies since the 1978 activity and a review of the historical seismicity in the area are also presented.

HISTORICAL SEISMICITY

The fault system defining the Eastern Front of the Sierra Nevada (EFSN) generated an earthquake of magnitude about 8 in 1872, which was accompanied by 110 km of identified fault rupture on the EFSN extending southward from a point about 20 km south of Bishop. One of the largest aftershocks (M6.9), of the 1872 earthquake, occurred two weeks after the mainshock and was much more destructive in Round Valley, about 20 km northwest of Bishop, than in the mapped rupture zone (Topozada *et al.*, 1980). This suggests that surface rupture might have extended 40 km northward of that shown on the Fault Map of California (Jennings, 1975). Jennings (personal communication) indicated that the data used in defining the extent of the 1872 rupture is not sufficiently detailed to rule out this possibility.

During the present century, the region within 50 km southeast of Long Valley caldera has experienced the greatest concentration of earthquakes ($M \geq 5.5$) of any region along the entire 600 km EFSN (Figure 1). The location of this intense seismicity indicates that the region near the northern end of the 1872 fault rupture is stressed. Earthquakes of $M \geq 5.5$ have occurred within this region in 1910 (M5.5), 1912 (M5.5), 1927 (M6.0), 1938 (M5.7), 1941 (M5.8, 5.5, 6.0), 1961 (M5.1, 5.3), 1978 (M5.8), and 1980 (M6.3, 6.0, 6.4, 5.6, 6.3). The magnitudes of the earthquakes of 1910 and 1912 were determined from intensity data by Topozada *et al.* (1978) and local earthquakes of this size (M5.5) were not adequately identified before 1910. During the past 70 years, earthquakes of M5.5 to 6.0 have occurred in this region every decade or two.

The earthquake sequence of May, 1980 represents the greatest seismicity on the EFSN during this century. In the highly seismic region within 50 km southeast of Long Valley caldera, the May 1980 earthquakes have occurred furthest to the northwest, where the southern rim of the

caldera offsets the EFSN. No earthquakes of $M \geq 5$ are known within the geothermally active Long Valley caldera.

SEISMICITY RELATED TO LAKE CROWLEY

Lake Crowley is within the area of intense seismicity southeast of Long Valley caldera. Topozada (1979) has pointed out that much of this seismicity coincided closely with the filling of Lake Crowley in 1941, and with the unprecedented refilling of the lake following the 1976-1977 drought. Figure shows that filling the lake in 1941 was immediately followed by five earthquakes of magnitudes 5 to 6, and that the unprecedented refilling in 1978 was immediately followed by two earthquakes of magnitudes 5.8 and 5.3 (all <10 km from dam).

These observations suggest that even shallow (34 meters) and small capacity (226.4×10^6 meters³) reservoir located in a seismically active area might induce earthquakes as large as M6. Earthquakes of magnitude 5 to 6 related to similar small reservoirs in seismically active areas have been reported by Galanopoulos (1966) for Lake Marathon in Greece, and by Topozada and Cramer (1978) for Lake Mendocino in California.

Figure 2 shows that the seismicity near Lake Crowley is naturally high and, regardless of the lake levels, earthquakes of magnitude 5.5 to 6.0 have occurred at intervals of 10 to 20 years since 1910. The May 1980 earthquakes were unrelated to Lake Crowley water levels, and represent a marked increase over the rate of earthquake occurrence since 1900.

CDMG STATION HISTORY

The initial response by CDMG to the Mammoth Lake swarms began in September 1979, after the M4.3 and M4.0 (CIT) event on September 24th. Figure 3 shows the local array of portable seismographs.

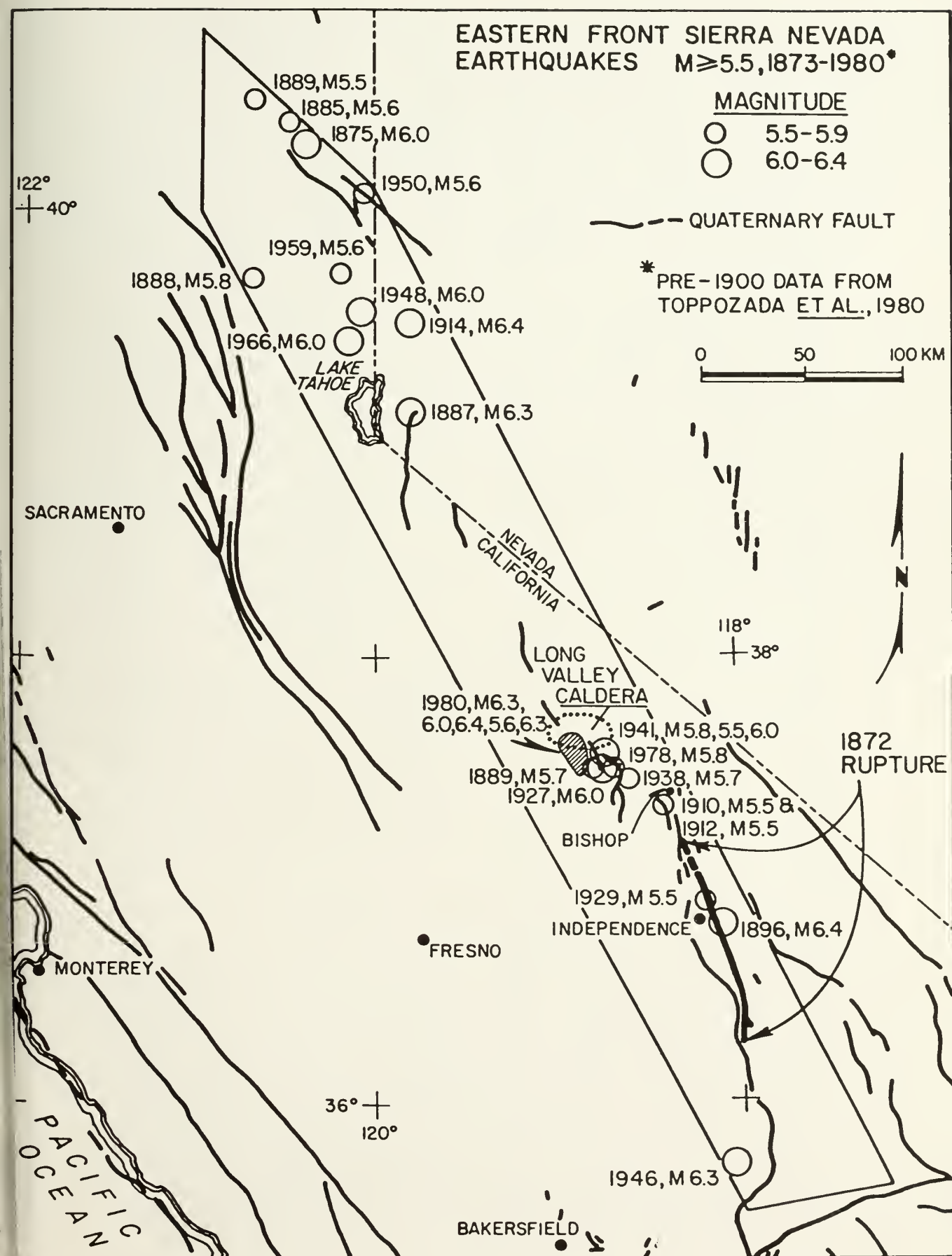
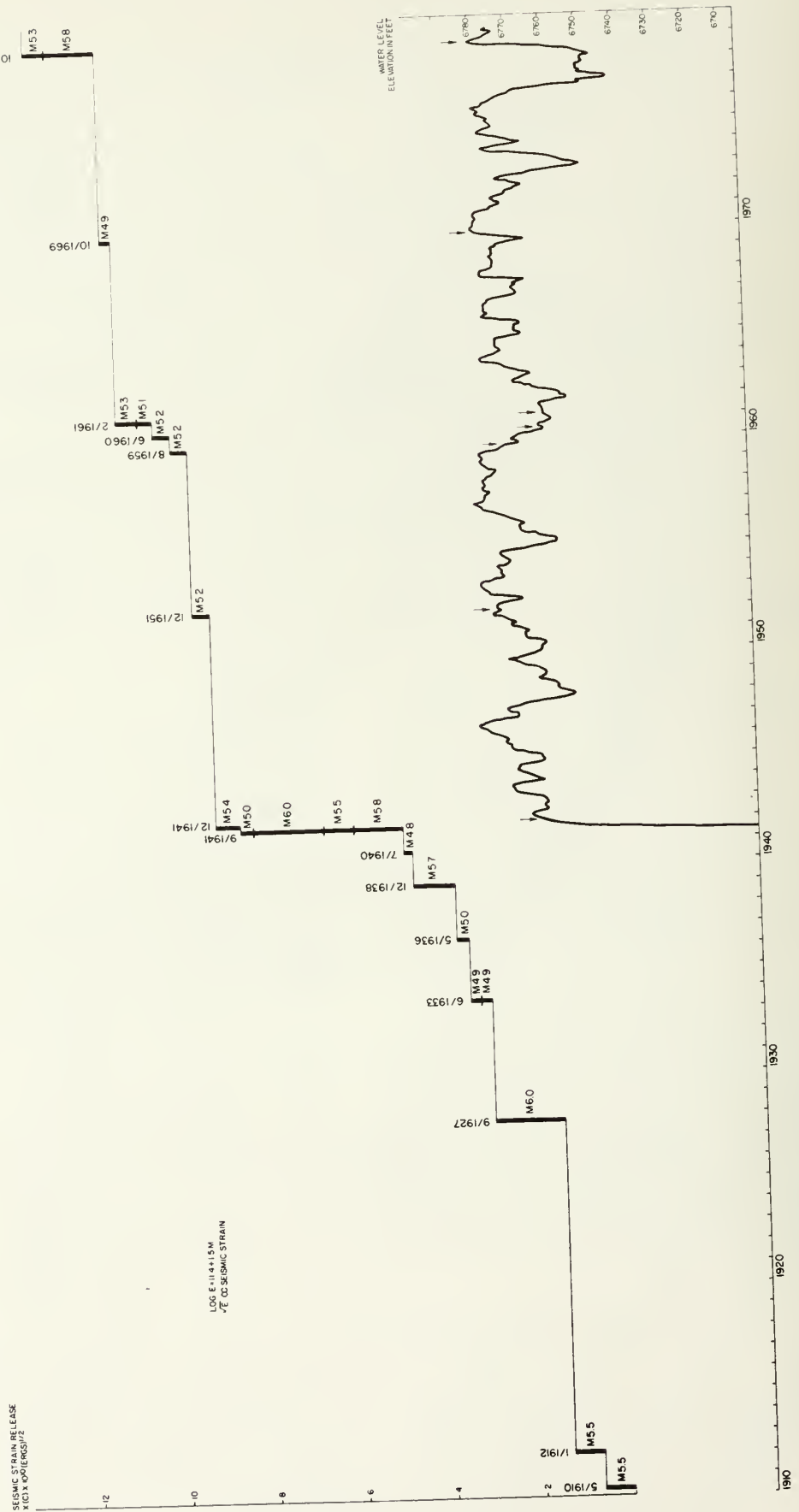


Figure 1.

Figure 2. LAKE CROWLEY WATER LEVELS AND SEISMIC STRAIN RELEASE WITHIN 40 KM OF LONG VALLEY DAM



ployed between September 25 and October 9, 1979. Following another M4 swarm on November 9th, a portable array was again stalled as shown in figure 3b. This portable array was removed on November 17 with the onset of winter. Three digital event recorders were left operating over the winter of 1979-80 in the Mammoth Lakes area. Another recorder was left operating at Bridgeport 80 km to the north. The other recording sites in the Mammoth Lakes area are shown in Figure 3c.

The local array was augmented immediately following the May 25, 1980, M6 earthquakes. The first four stations were stalled and operational on the evening of May 25 and the remainder were installed May 26. The augmented array as shown in figure 3d was operational to June 8. Since June 8, four digital event recorders in the Mammoth Lakes area plus the Bridgeport station to the north have continued in operation (figure 3e). All CDMG seismograph stations are listed in Table 1 along with their operational periods and type of recording equipment.

In addition to sensitive seismographs in the Mammoth Lakes area, existing strong-motion accelerograph coverage was augmented following the May 25, 1980 sequence (figure 3f and Table 1). Many of the CDMG strong-motion stations provided important records for analysis of the larger ($M \geq 5$) events of the sequence (Pen, 1980, this volume).

DATA REDUCTION

Arrival time and first motion data for the events presented in this report have been obtained from the regional stations recorded on Develocorder film at the California Department of Water Resources (CDWR) Earthquake Engineering Office in Sacramento. This regional coverage consists of selected telemetered stations operated by University of California, Berkeley (UCB), California Institute of Technology (CIT), U.S. Geological Survey (USGS), University of

Nevada, Reno (UNR), and CDWR. These data were augmented with arrival time and first motion data from CDMG event recorder (Sprengnether DR 100), smoke drum (Sprengnether MEQ-800), and accelerograph (Kinematics SMA-1) records from Mammoth Lakes stations. For certain key earthquakes, additional phase and first motion data from CIT's Tinemaha (TIN) station and UNR's Mono Lake (MON) station have been obtained directly from CIT and UNR.

P and S wave arrivals were read to the nearest 0.05 second, in most cases (the nearest 0.1 second at TIN), and hypocentral locations were determined using Lahr's (1979) HYPOELLIPSE computer program. Final locations were determined by applying a pseudo master-event technique in order to improve relative locations among events with respect to the largest events of the May 25 sequence ($M \geq 5$). This technique used the mean of a given station's weighted residuals from A and B quality solutions (see Appendix I for definition) for $M \geq 5$ events as a station correction in order to reduce systematic errors due to site and path geology or misidentification of arrivals. Only arrivals at stations within 225 km of the epicenter were used in the final hypocentral determinations.

The velocity model employed in the final location process (Table 2) is essentially that of Eaton (1966) for the east side of the Sierra Nevada modified in the near surface by the refraction results of Hill (1976) for the Long Valley Caldera. In order to allow for the thicker surface layer inside the caldera than outside the caldera, a dual velocity model was employed. Stations located in Long Valley have a 2.5 km thick surface layer while stations outside have only a 1.0 km thick surface layer as indicated by Hill's data. It is important to make this distinction between stations inside and outside the caldera, because travel time delays associated with the thicker surface layer in the caldera will tend to bias epicenters outward from the caldera (to the south in this case). A V_p/V_s ratio of

Figure 3a
CDMG SEISMOGRAPH STATIONS
25 Sept - 21 Oct
1979

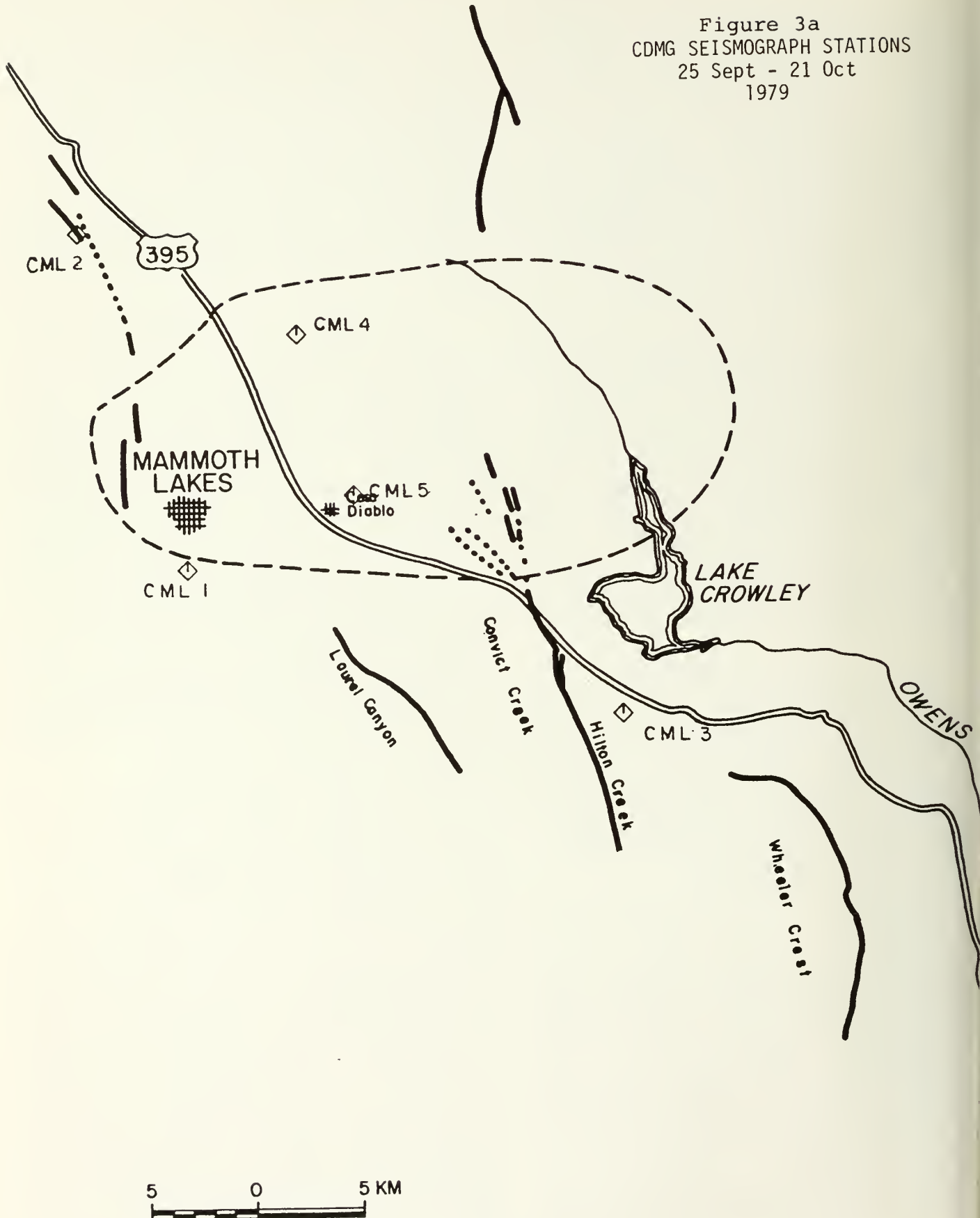


Figure 3b
CDMG SEISMOGRAPH STATIONS
11 Nov - 17 Nov
1979

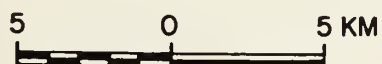
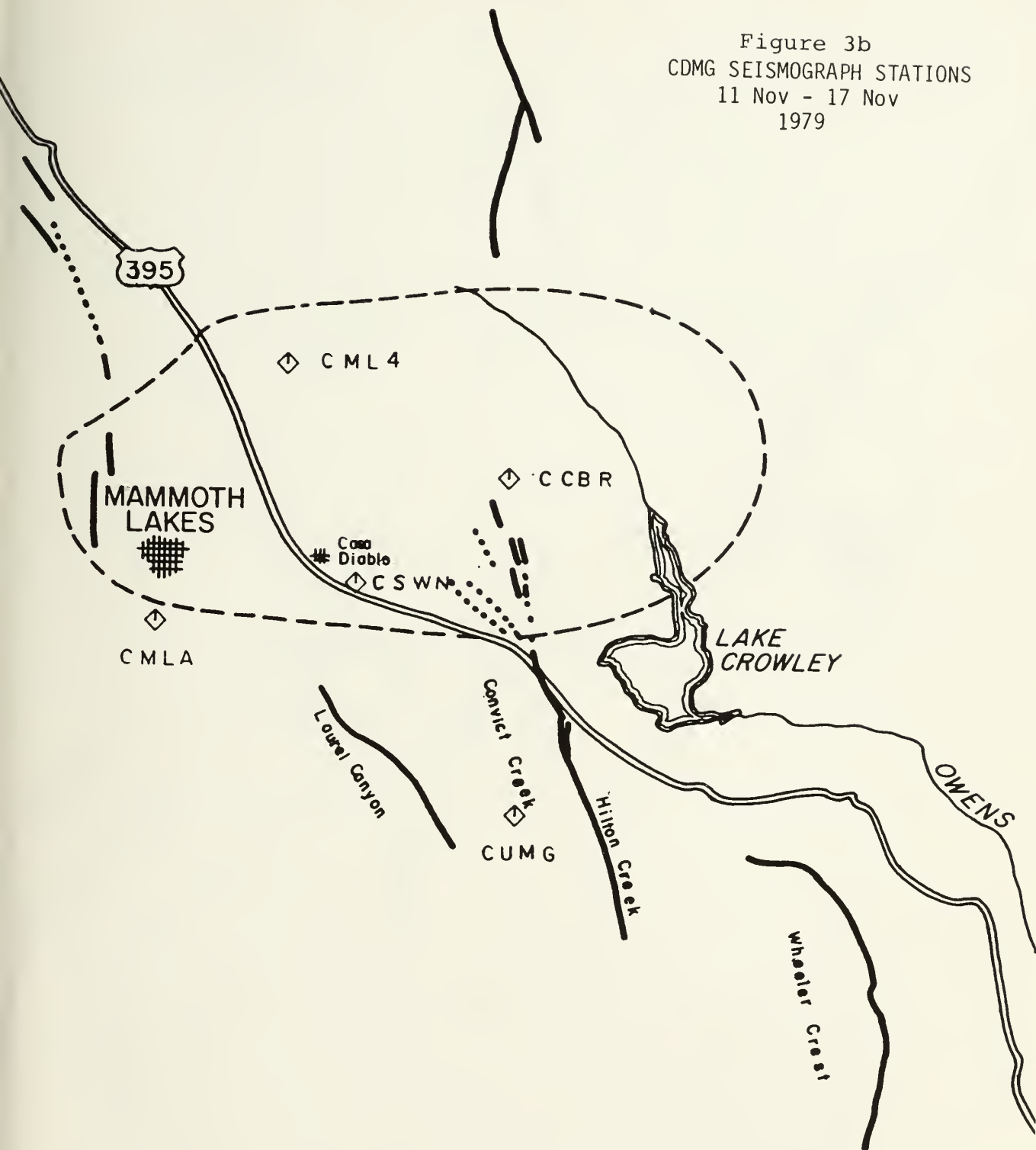


Figure 3c
CDMG SEISMOGRAPH STATIONS
18 Nov 79 - 25 May 80

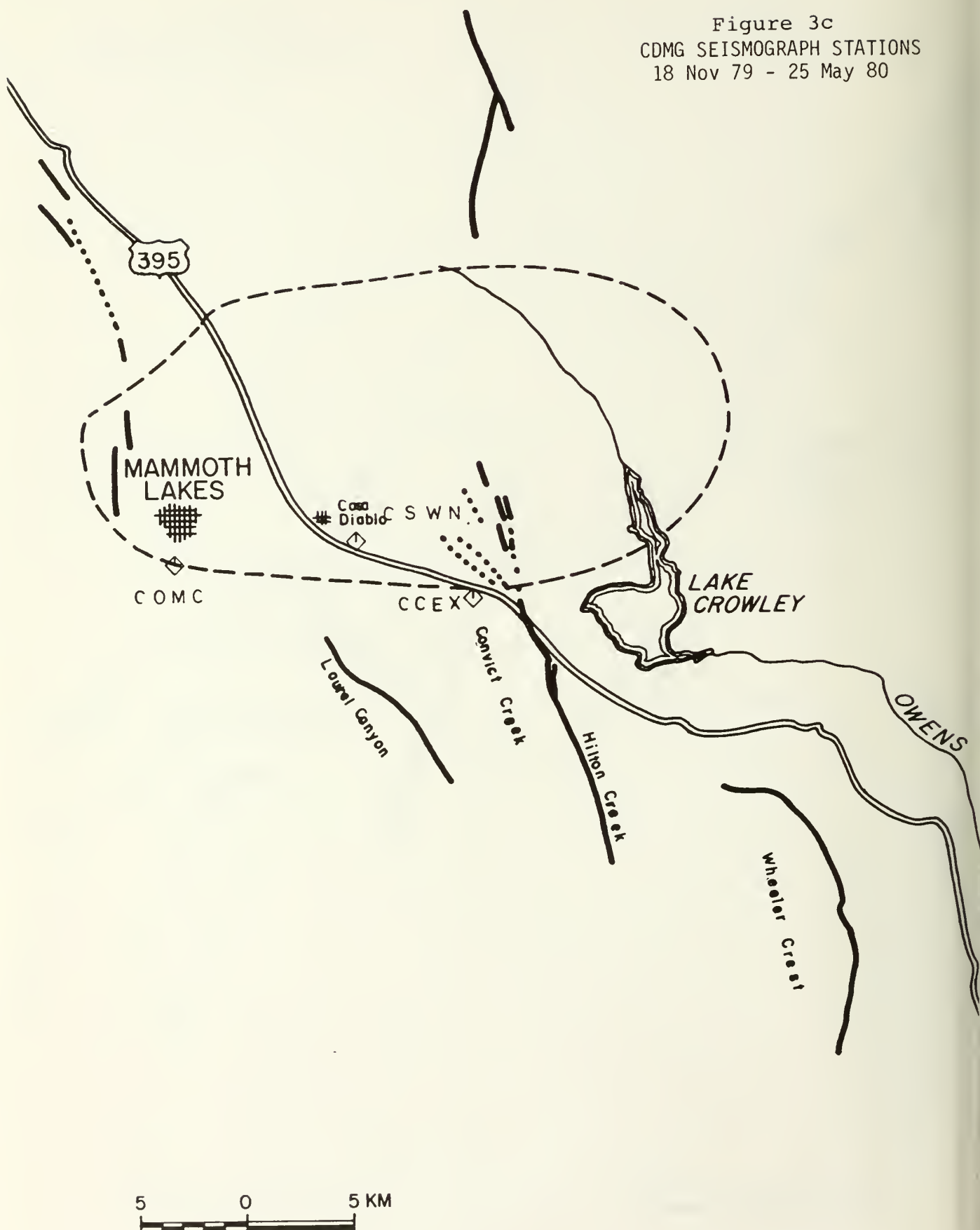


Figure 3d
CDMG SEISMOGRAPH STATIONS
26 May - 8 June
1980

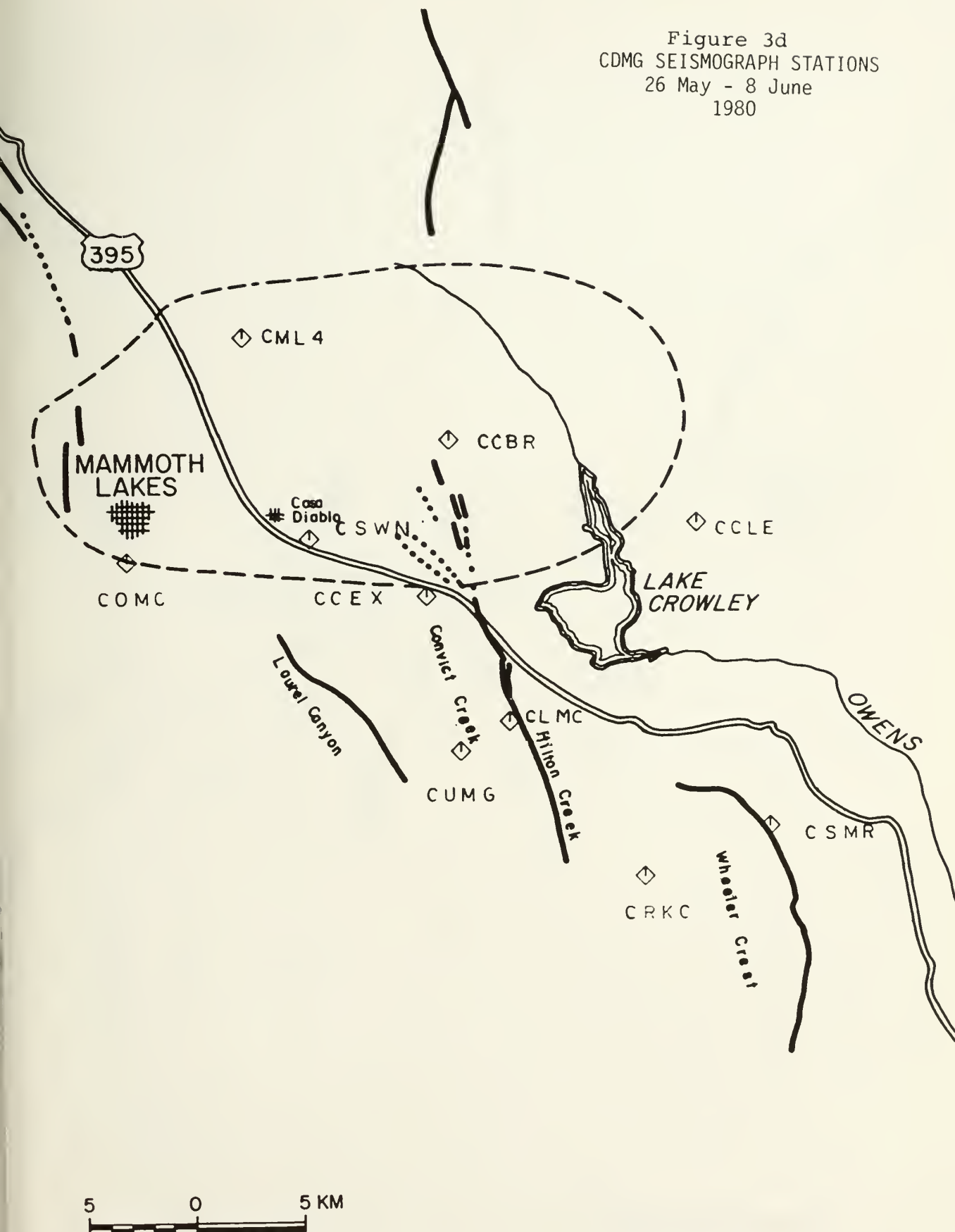


Figure 3e
CDMG SEISMOGRAPH STATIONS
9 June - present
1980

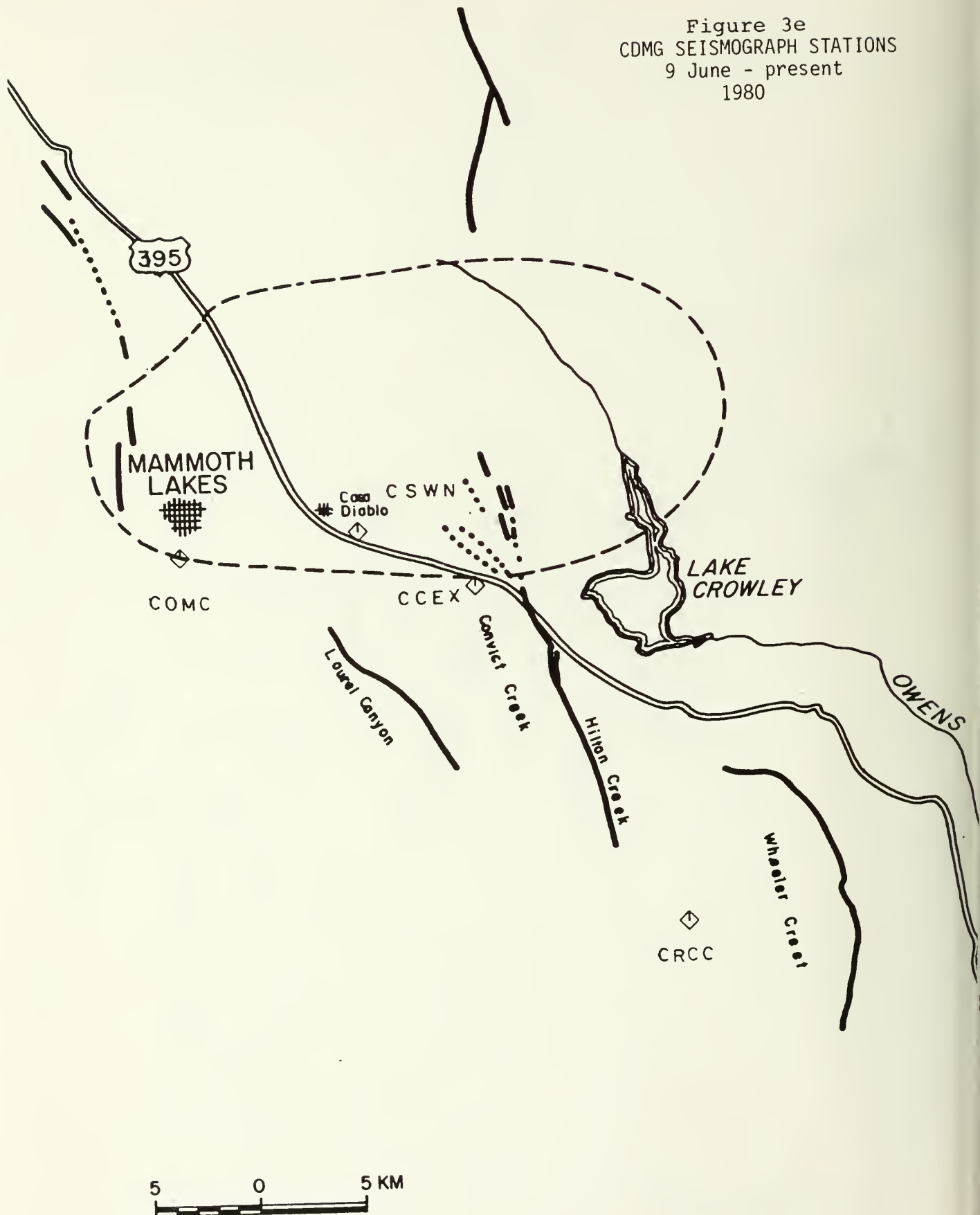


Figure 3f
CDMG ACCELEROGRAPH STATIONS
1978 - 1980

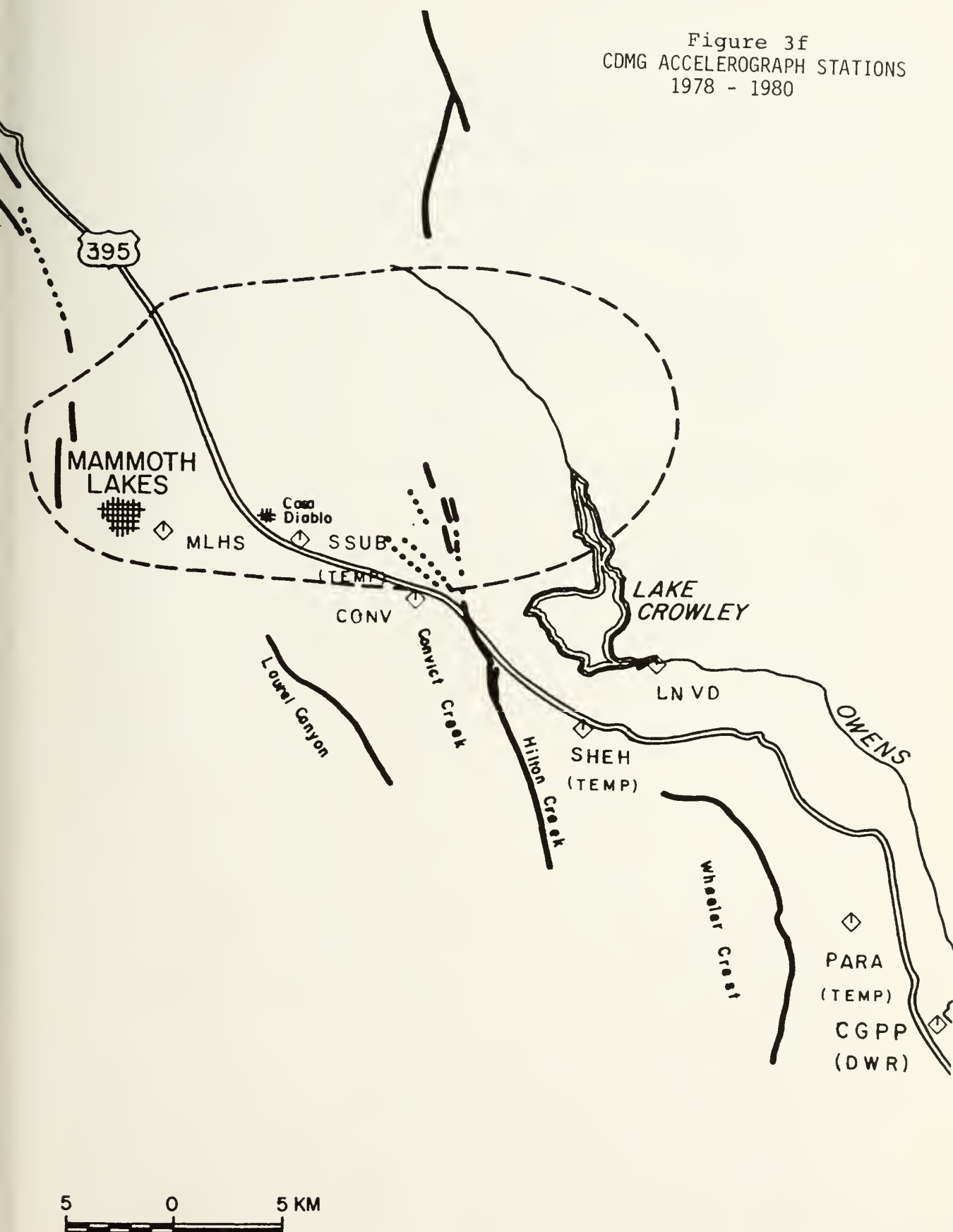


TABLE 1

CDMG SEISMOGRAPH STATIONS - MAMMOTH LAKES, CA.

STN CODE	LAT N	LONG W	ELEV (M)	TYPE	OPERATIONAL DATES (UT)
CML1	37 37.38	118 59.12	2545	SMOKE	25 SEPT - 21 OCT 79
CML2	37 45.94	119 02.54	2676	DIGITAL	27 SEPT - 09 OCT 79
CML3	37 33.64	118 45.40	2256	DIGITAL	27 SEPT - 20 OCT 79
CML4	37 43.34	118 55.56	2265	SMOKE	28 SEPT - 21 OCT 79
				DIGITAL	12 NOV - 17 NOV 79
				SMOKE	26 MAY - 8 JUN 80
CML5	37 39.25	118 53.82	2333	DIGITAL	13 OCT - 21 OCT 79
CCBR	37 40.76	118 49.11	2121	DIGITAL	12 NOV - 17 NOV 79
				SMOKE	26 MAY - 8 JUN 80
CCEX	37 36.84	118 49.83	2158	DIGITAL	29 NOV 79 - PRESENT
CCLE	37 38.65	118 41.38	2182	SMOKE	27 MAY - 8 JUN 80
CLMC	37 33.69	118 47.28	2351	SMOKE	26 MAY - 27 MAY 80
CMLA	37 37.34	118 59.27	2560	SMOKE	12 NOV - 16 NOV 79
COMC	37 37.71	118 59.22	2438	DIGITAL	30 NOV 79 - PRESENT
				SMOKE	28 MAY - 8 JUN 80
CPWT	38 16.64	119 15.14	1996	DIGITAL	15 NOV 79 - PRESENT
CRCC	37 28.17	118 43.32	2859	DIGITAL	9 JUN 80 - PRESENT
CRKC	37 29.77	118 43.11	2707	SMOKE	27 MAY - 8 JUN 80
CSMR	37 31.00	118 39.16	2182	SMOKE	27 MAY - 8 JUN 80
CSWN	37 38.29	118 53.50	2188	DIGITAL	11 NOV 79 - PRESENT
				SMOKE	12 NOV - 16 NOV 79
				SMOKE	26 MAY - 8 JUN 80
CUMG	37 32.96	118 48.80	2475	DIGITAL	12 NOV - 16 NOV 79
				SMOKE	26 MAY - 8 JUN 80
BENT	37 49.08	118 28.50	1643	ACCEL	MAR 74 - PRESENT
CGPP	37 26.30	118 33.37	1341	ACCEL	75 ?
CONV	37 36.84	118 49.83	2158	ACCEL	MAR 74 - PRESENT
LNVD	37 35.28	118 42.30	2072	ACCEL	NOV 75 - PRESENT
MLHS	37 38.46	118 57.77	2396	ACCEL	FEB 77 - PRESENT
PARA	37 28.86	118 36.12	1494	ACCEL	OCT 78 - PRESENT
SHEH	37 33.65	118 44.58	2155	ACCEL	MAY 80 - PRESENT
SSUB	37 38.29	118 53.50	2188	ACCEL	MAY 80 - PRESENT

TABLE 2

VELOCITY MODELS FOR LOCATING MAMMOTH LAKES EARTHQUAKES

VELOCITY (KM/S)	OUTSIDE CALDERA DEPTH TO TOP (KM)	INSIDE CALDERA DEPTH TO TOP (KM)
4.0	0.0	0.0
6.0	1.0	2.5
6.4	13.0	13.0
6.9	27.0	27.0
7.9	50.0	50.0

1.71 was assumed in order to incorporate S-wave data. No elevation corrections were applied to the arrival time data so listed depths are relative to the local ground surface.

Magnitudes listed were determined by CIT and UCB. They are preliminary Richter magnitudes and the source is indicated by the letter P, for Pasadena, or B, for Berkeley, following the magnitude listed in Appendix I. The magnitudes shown in Figure 1 for the earthquakes of $M \geq 5.5$ are the mean of CIT and UCB determinations.

MAY 25, 1980 SEQUENCE

Figure 4 shows the locations of all $M \geq 5$ earthquakes in the May 25 sequence up to June 1, 1980. Each event is sequentially numbered beginning with the first $M 6$ event at 1633 GMT on May 25. Many of these locations employed CDMG strong-motion accelerograph data and all are B quality solutions, except events 2 and 4 which are D quality (see Appendix I, Table 3). Event 2 is a $M 5$ earthquake that occurred at 1935 GMT within three minutes of event 1, and was located using only strong-motion records from CONV, LNVD, and MLHS, and the CDMG Bridgeport event recorder at CPWT, because the sensitive records were saturated from event 1.

Hypocentral depths for the events in figure 4 are generally less than 10 km. The exceptions are events 3, 5, and 10 which have hypocentral depths of 13.8, 16.4, and 14.2 km respectively.

The greatest energy release of the May 25 sequence is clearly west of the Hilton Creek fault, a major east dipping normal fault of the EFSN. In fact, no $M 5$ events occur near the Hilton Creek fault until late in the sequence (event 11). The Hilton Creek fault therefore does not appear to be the causative fault for this sequence. Relative epicenters shown in figure 4 should be accurate to within one kilometer. The entire pattern could be in error in the absolute sense by 2 km.

Initially, the largest events occurred along an east-west trend near the southern boundary of the Long Valley Caldera (events 1-4). Activity then began migrating southward from the caldera boundary with the occurrence of the third $M 6$ earthquake on the 25th of May. Three of the four largest events (1, 5, and 10) align along a north-south trend. It is interesting that activity at the $M 5$ level did not occur south of the caldera boundary until after the third $M 6$ of the sequence (event 5), the first major event south of the caldera. Also, activity at the $M \geq 5$ level near Laurel Canyon and near the Hilton Creek fault did not occur until after the third $M 6$ of the sequence. This suggests that the activity near Laurel Canyon and the Hilton Creek fault may be indicative of readjustment occurring along other faults as a result of major displacements along the fault bounding the caldera on the south and along faults located near the third and fourth $M 6$ events of the sequence.

Figure 5 shows epicenters for 53 of the $200 \ 3.5 \leq M < 5$ aftershocks for the period May 25 - June 8, 1980. These are only the A & B quality (see Appendix I for definition) preliminary solutions determined thus far using phase data from CDMG local stations and regional stations recorded by CDWR. The station corrections used in these solutions were determined from the $M \geq 5$ events as described under Data Reduction. For this specific group of events, only arrival time data from stations within 160 km of the epicenters were used in the solutions. Hypocentral depths range from less than 1.0 km to 12 km, usually centering between 5 and 10 km.

The pattern of epicenters shown in figure 5 is diffuse, but almost entirely west of the Hilton Creek fault and near south of the southern boundary faults of the Long Valley caldera. This distribution is very similar to that for the $M \geq 5$ events as shown in figure 4. Only a few epicenters are near the Hilton Creek fault, and those are generally near its juncture with the southern boundary faults of the caldera. There is a

Figure 4
MAMMOTH LAKES EARTHQUAKES
25 May - 31 May 1980
Magnitude ≥ 5.0

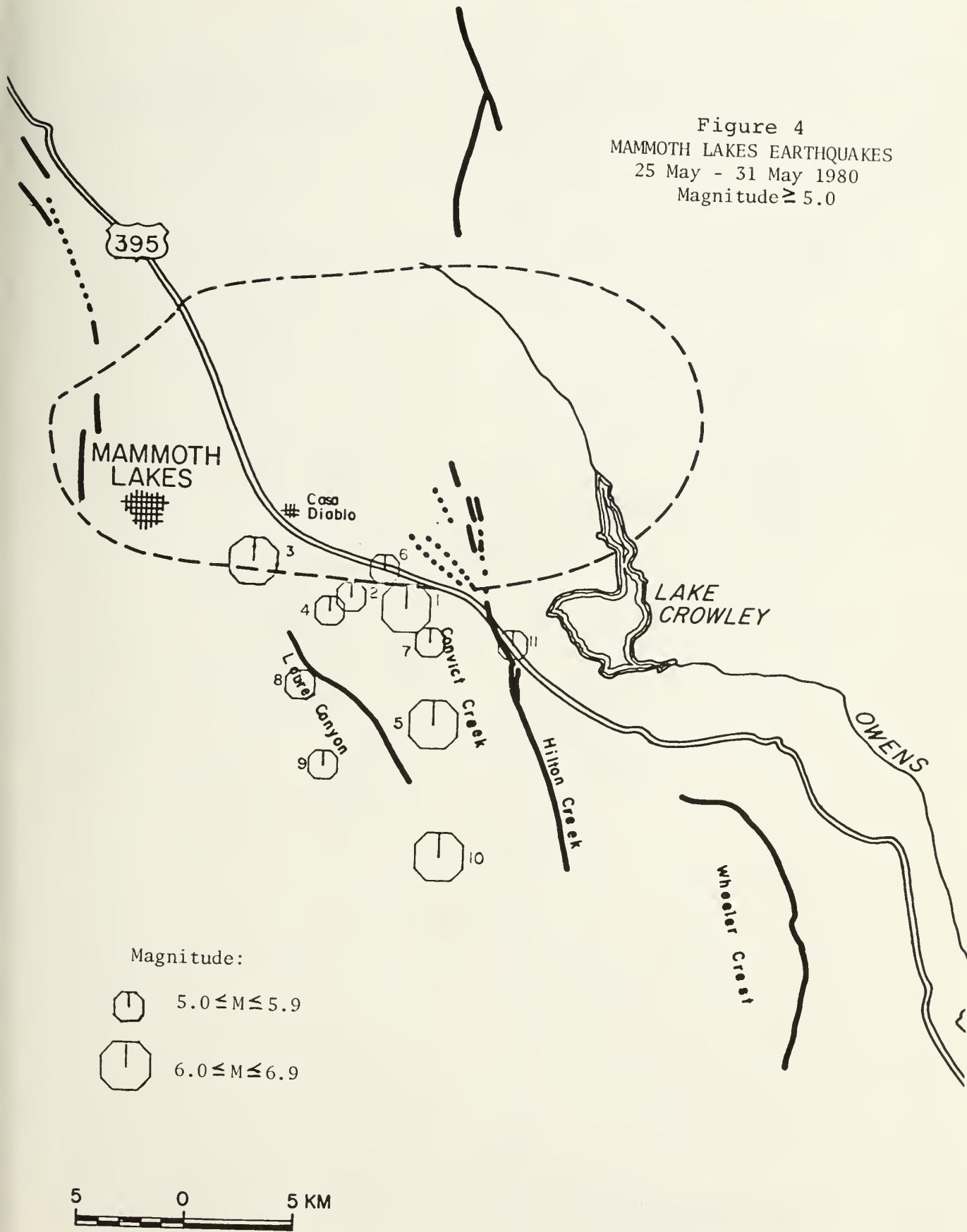
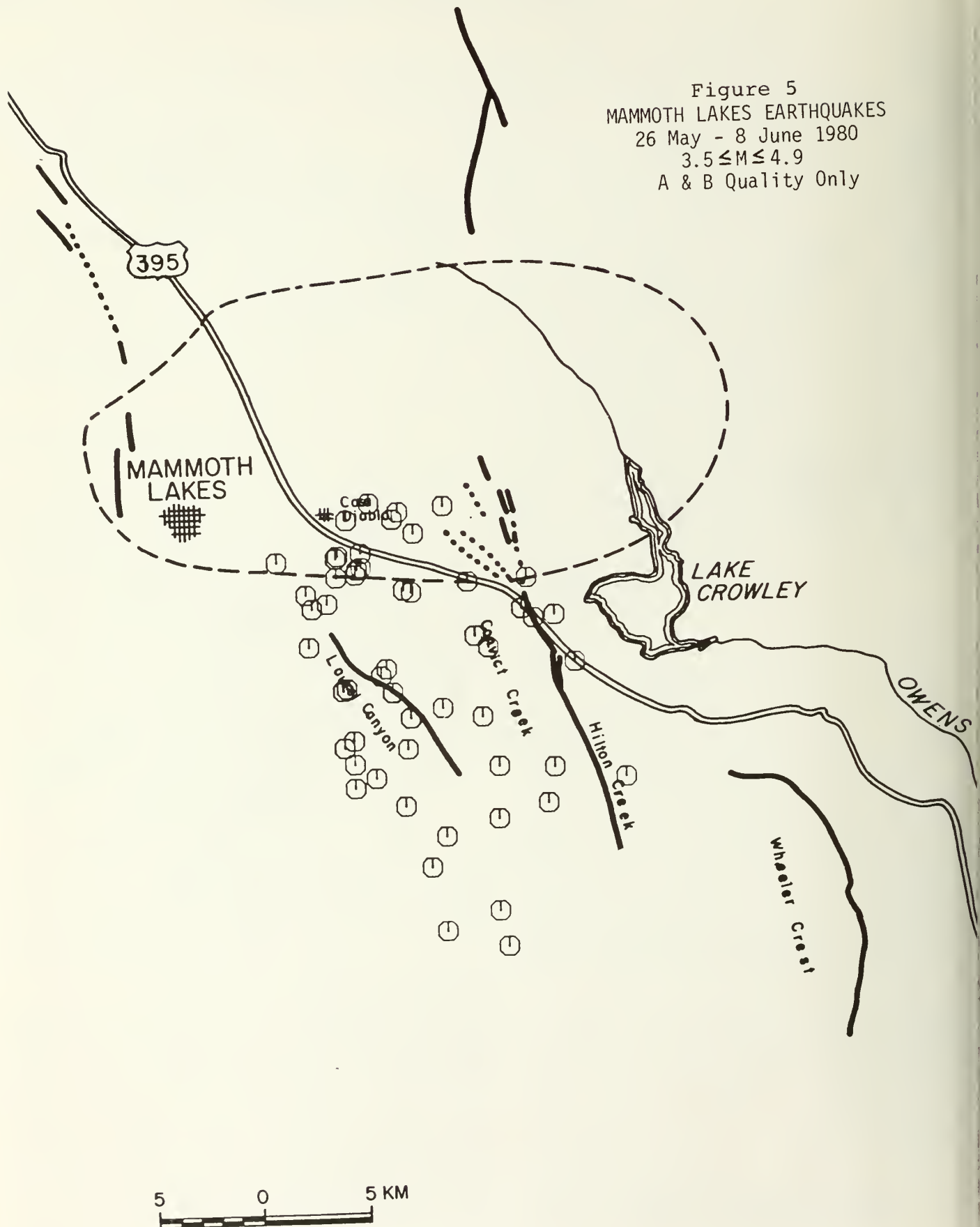


Figure 5
MAMMOTH LAKES EARTHQUAKES
26 May - 8 June 1980
 $3.5 \leq M \leq 4.9$
A & B Quality Only



clustering of events near Casa Diablo and near Laurel Canyon. Considering the high quality of the solutions, this pattern of aftershock activity suggests movement on several faults that form a complex zone of deformation.

JUNE 1979 - MAY 1980 SWARMS

The May 25, 1980, sequence was preceded over a year by M3.5 to 4.5 earthquake swarms in the Mammoth Lakes area. The first M4 swarm occurred on June 16, 1979; however, M3½ swarms occurred prior to June 1, 1979, on February 5, February 7, March 12, March 14, and May 27, 1979. Figure 6 shows just the M ≥ 4 events in the Mammoth area. Some of the earlier data have poor local station coverage, but location qualities are generally B and C, except for events 7 and 14 which are quality D (see Appendix I, Table 2). Relative epicenter accuracy, however, is believed to be about one kilometer. Hypocentral depths range between 0 and 10 km.

The epicenters in figure 6 have been numbered sequentially and generally tend to cluster near the southern boundary of Long Valley caldera. Earthquake activity at the M4 level shows an interesting migration with time. Event 1 is the June 16th earthquake which was located south of the caldera and west of Laurel Creek Canyon. Events 2-4 occurred on September 1 and 24th just west of Casa Diablo. Events 5-8 occurred on November 9th and 10th near and to the east of Casa Diablo. Events 9, 10, and 11, on November 26th and December 6th and 8th, respectively, continued the apparent eastward migration of activity along the southern caldera boundary. The pattern changed at the end of December and in January with events 12 and 13, which are widely separated from previous activity. Event 12 may have been on one of the causative faults of the May 25th, 1980, M6 sequence and event 13 is near the juncture of the Hilton Creek fault with the southern boundary of the caldera. Two months of quiet at the M4 level ended on March 20th and 27th by events 14-16 near Casa Diablo. Events 17

and 18 occurred on May 14th and 17th near Hot Creek and Mammoth Airport. These two events are north of the first M6 which occurred a week later. Events 19 and 20 occurred close together, east of Casa Diablo, on May 18th and early on May 25th. Event 20 is the immediate foreshock to the M6 sequence, and occurred about 12 hours before the first M6 earthquake. This time-history suggests migration of earthquakes along the southern boundary faults of the caldera to the east of Casa Diablo.

A deep (5265') geothermal test well was completed in August 1979 and the first M4 earthquake swarm near Casa Diablo occurred in September. The epicenters of the three M4 earthquakes of the September swarm are located within 3 km of the well (figure 6, events 2-4). The coincidence of the inception of the Casa Diablo swarm with the completion of the well is difficult to explain, because no production or injection took place in the well.

Figure 7 shows a histogram of daily seismicity, plotted as square root of energy, from January 1978 through May 1980. Ryall and Ryall (1980, and this volume) reported a decrease in seismicity along the Sierra Nevada-Great Basin boundary from October 1977, to September 1978, followed by a general increase in activity along the entire zone. As shown in figure 7, seismic activity in the Mammoth area was consistent with this observation, remaining at a low level prior to October 1978. As pointed out by Ryall and Ryall, periods of seismic quiescence can be associated with precursory phenomena preceding large earthquakes (e.g. see Kelleher and Savino, 1976; Ishida and Kanamori, 1978 and 1980). After October, 1978, the seismic activity intensified in the Mammoth area, particularly during November and December, 1979. Clustering of activity in space and time has been suggested by McNally (1978, 1980) as an intermediate-term precursor to larger earthquakes in California. However, as pointed out by Ishida and Kanamori (1980), this pattern of quiescence followed by clustering is not always a definite indicator of a large

Figure 6
MAMMOTH LAKES EARTHQUAKES
1 June 79 - 25 May 80
Magnitude ≥ 4.0

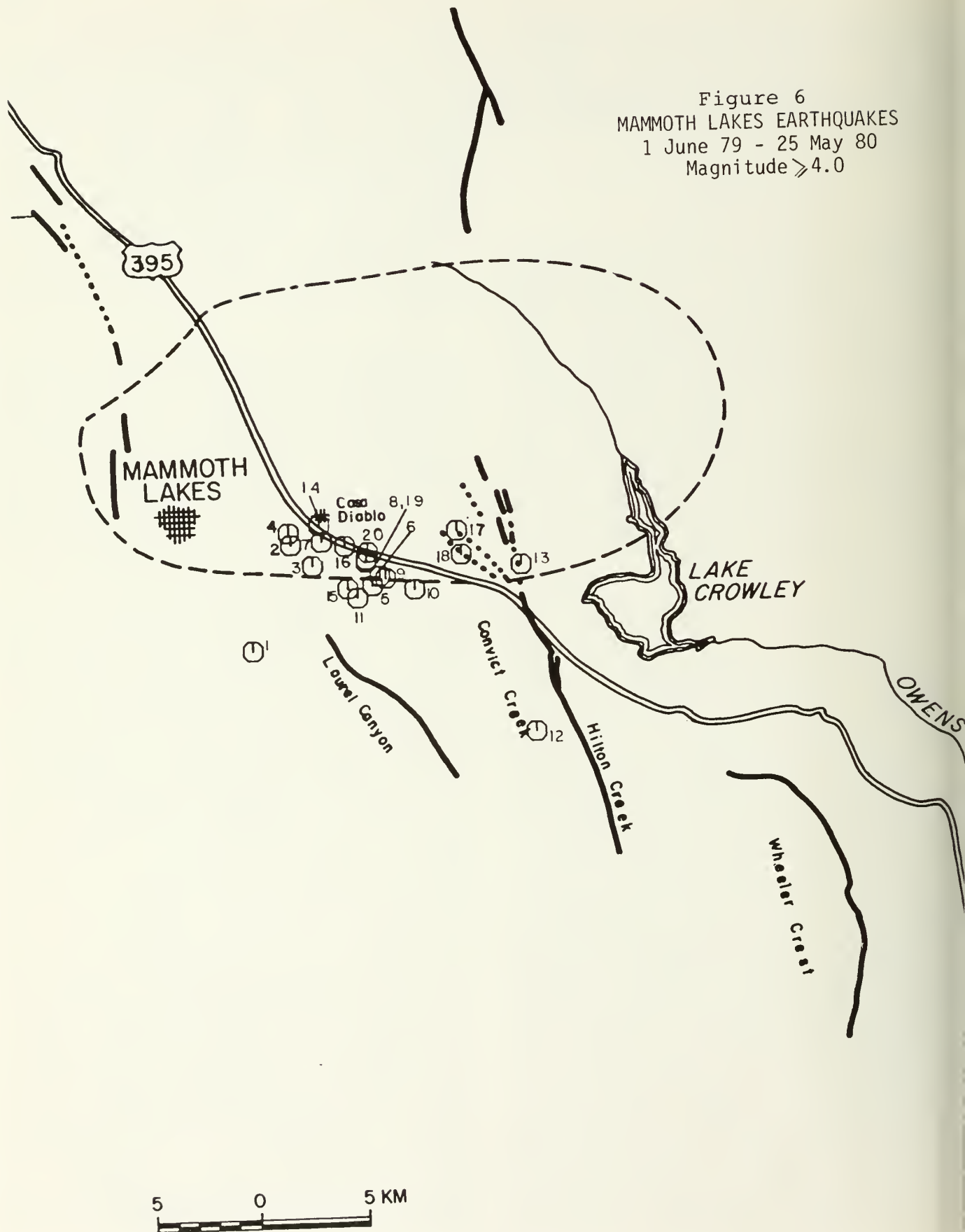




Figure 7. Square root of seismic energy released, Bishop - Mammoth Lakes, 1978 - May 1980.

earthquake. Thus the temporal pattern and spatial migration of activity at Mammoth, as described above, may have been precursory to the M6 earthquakes. But, the seismicity pattern in figures 6 and 7 gives no clear indication of when or if these large events were to occur. (See Appendix III for a brief discussion of hot spring activity during this period.)

OCTOBER 1978 SEQUENCE

On October 4, 1978, a M5.8 earthquake occurred south of Lake Crowley. Aspects of this earthquake have been previously reported by Fuis *et al.* (1979) and Topozada (1979). Figure 8 shows CDMG epicenters for all the $M \geq 4$ events for October, 1978, through January, 1979, numbered sequentially. Location quality is generally poor due to lack of close in stations (Appendix I, Table 1). However, strong-motion records from CDMG and Los Angeles Department of Water and Power accelerographs for the main shock (event 1) and for event 12 (January 24, 1979) provided valuable data that improved the solution quality to B (Appendix I). Events 1 and 12 were used as master events to improve the relative locations of the remaining $M \geq 4$ events of the sequence. Relative locations of the events shown in figure 8 are believed to be accurate to within 2 km.

The October events (1-10) cluster beneath the north end of Wheeler Crest (8 km south of Long Valley Dam at Lake Crowley) and appear to have a north-south trend, although, this may be an artifact of poor N-S station control. The two events in January (events 11 and 12) locate north and east, respectively, of the October cluster with the latter event possibly being on another feature. Hypocentral depths are generally greater than 15 km. Events 8 and 10 have focal depths of 11.8 km and events 5 and 11 have focal depths of 5.6 and 8.0 km respectively. These depth variations, with little variation in epicenter locations, particularly in an east-west direction,

suggest a near vertical crustal feature the cause of the 1978 activity, although the lack of near in depth control weakens this suggestion.

FOCAL MECHANISMS

Figure 9 shows individual focal mechanisms for selected larger events from 1978 through 1980. Shaded regions are compressional first motions. Mechanisms are lower hemisphere, equal-area projections. Each focal mechanism is reproduced with its first motion data in Appendix II, except for the focal mechanism of the October 4, 1978, M5.8 earthquake which was determined by G. Fuis (1979, oral communication).

The dominant sense of motion for the earthquakes is strike-slip with NE-tensional axes and NW-SE compression axes. This implies right-lateral motion on east-west faults or left-lateral motion on north-south faults. First motions for $M \geq 4$ events in the Mammoth area, from June 1979 through May 1980, were consistent with the first motion pattern shown for the 7 September and 20 November 1979, events. The similarity in focal mechanisms for the four M6 earthquakes in May, 1980, to the mechanism for the October 1978, M5.8 earthquake is quite remarkable.

There are suggestions of dip-slip movements in the focal mechanisms for the $M \geq 5$ events beneath Laurel Canyon near the Hilton Creek fault (events 8, 10, and 11, figure 4). However, the focal mechanisms are not well constrained and strike-slip cannot be ruled out with the data currently available from CDWR and CDMG records. Additional data from USGS local and regional stations should help to resolve this question. For this reason, these focal mechanisms have not been reproduced in this paper.

Figure 10 summarizes the previously published focal mechanisms for the area taken from Pitt and Steeples (1975) and Steeples and Pitt (1976). These mechanisms are both individual and composite

Figure 8
LAKE CROWLEY - MAMMOTH EARTHQUAKES
Oct 78 - May 79
Magnitude ≥ 4.0

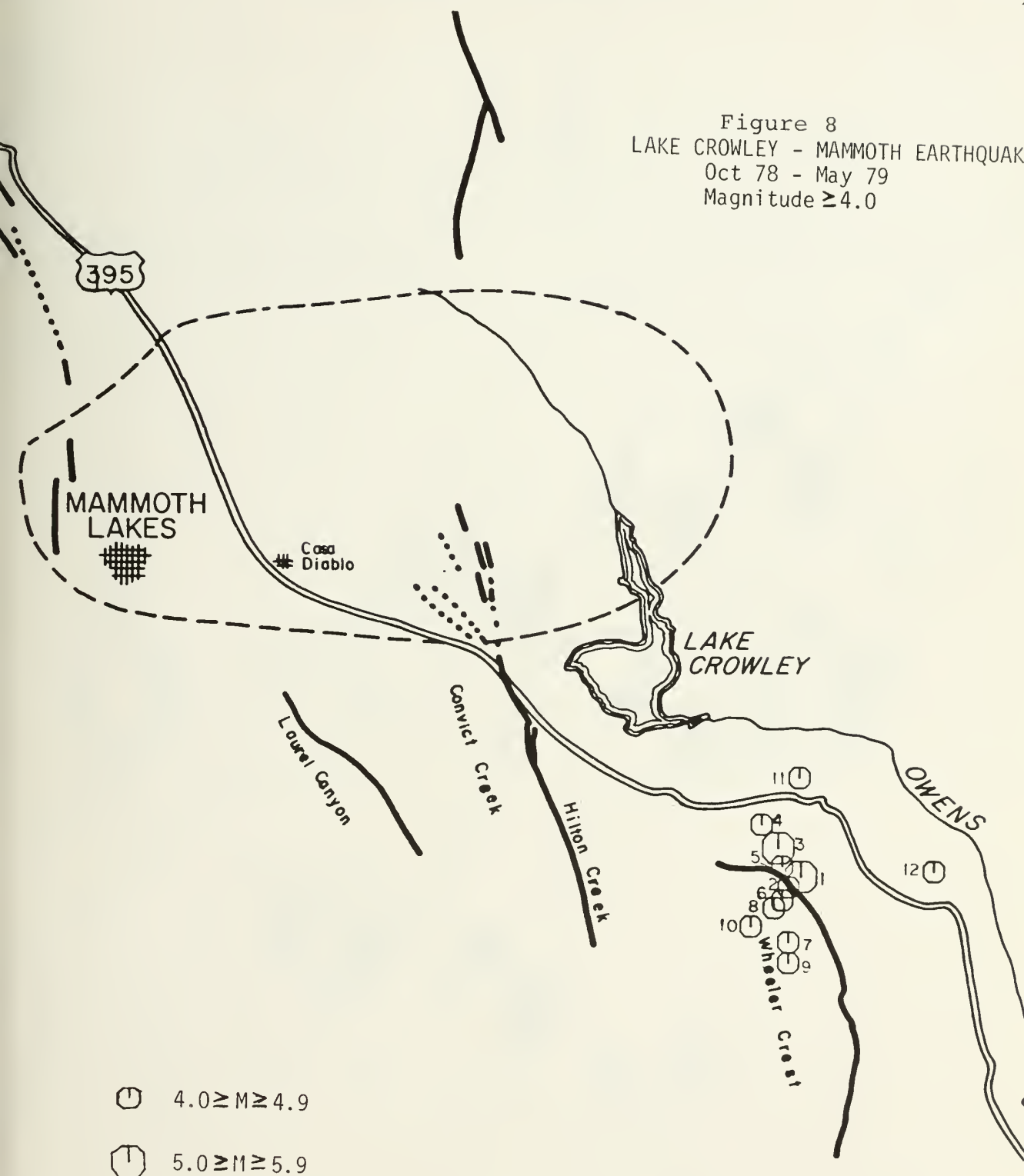


Figure 9
FOCAL MECHANISMS
1978 - 1980

Lower Hemisphere Projection
Compressional First Motions Shaded

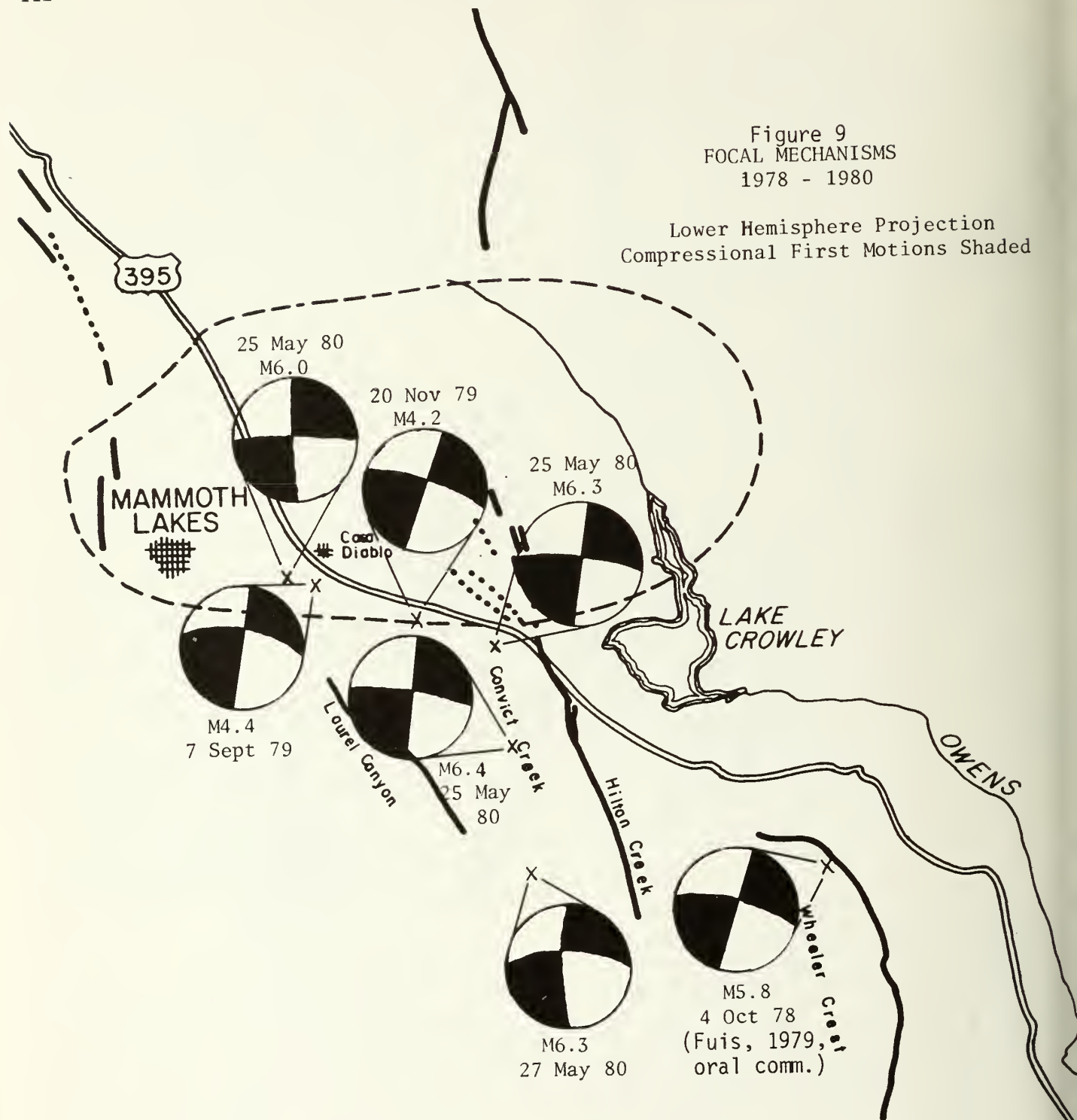


Figure 10
FOCAL MECHANISMS
1971 - 1973

Lower Hemisphere Projection
Compressional First Motions Shaded

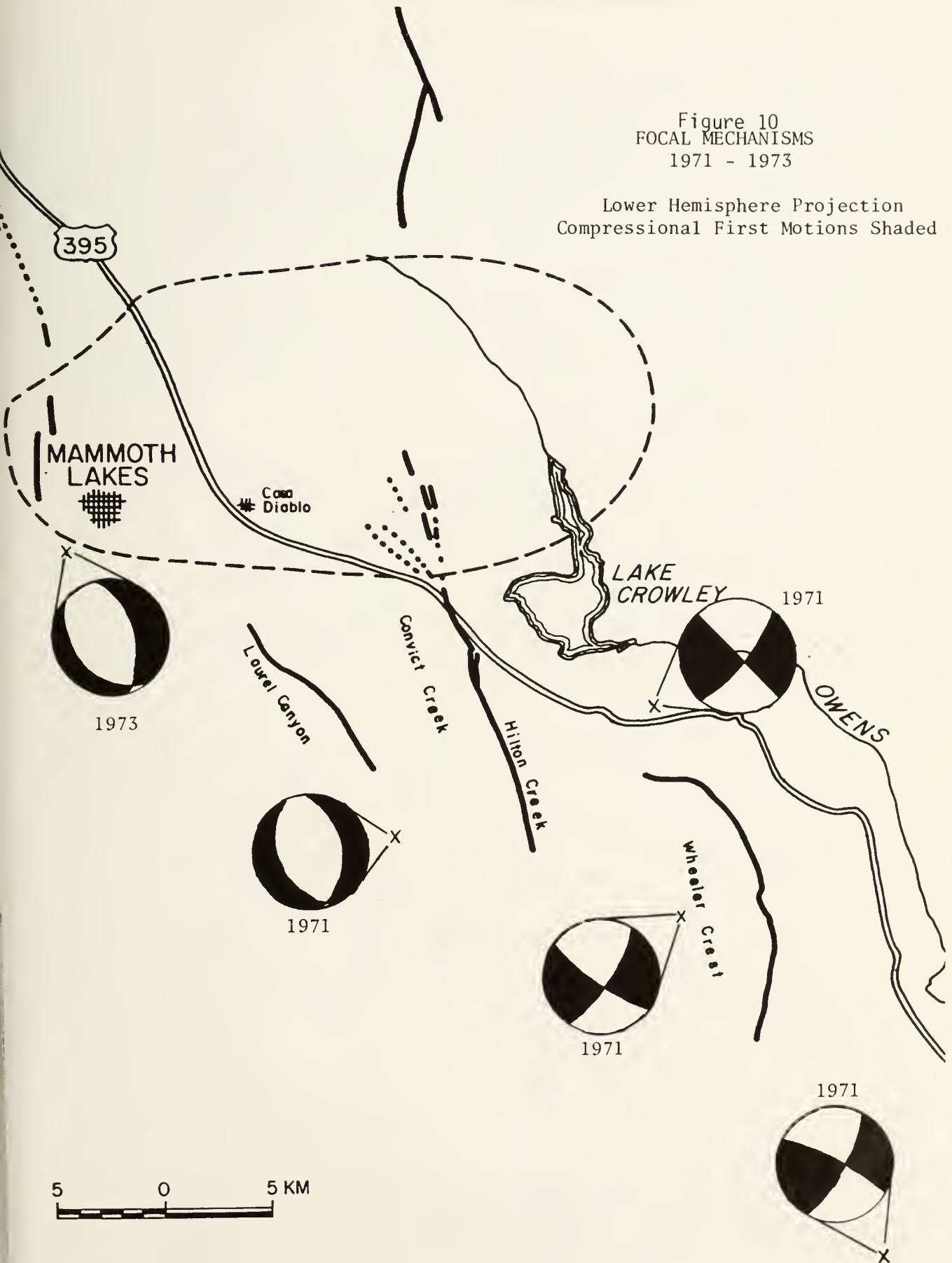
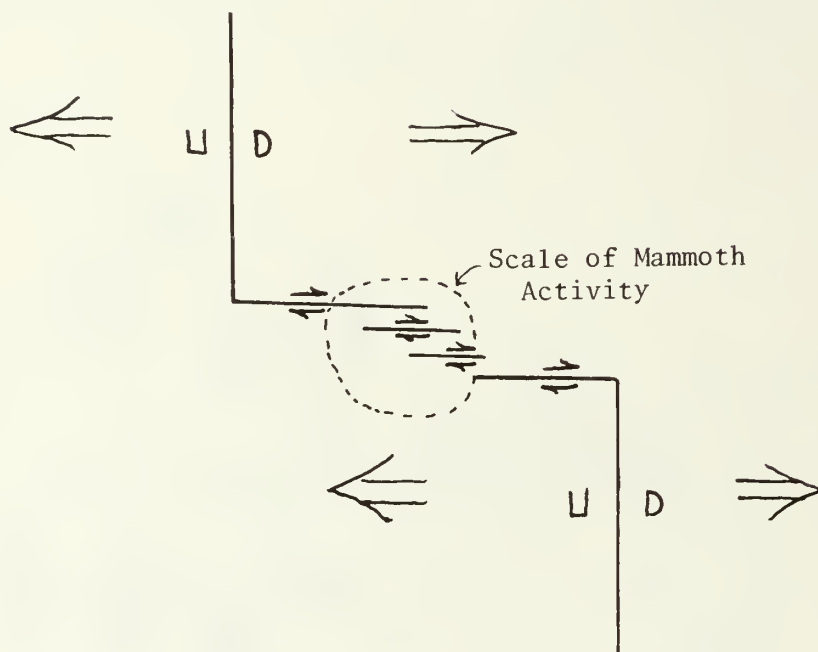


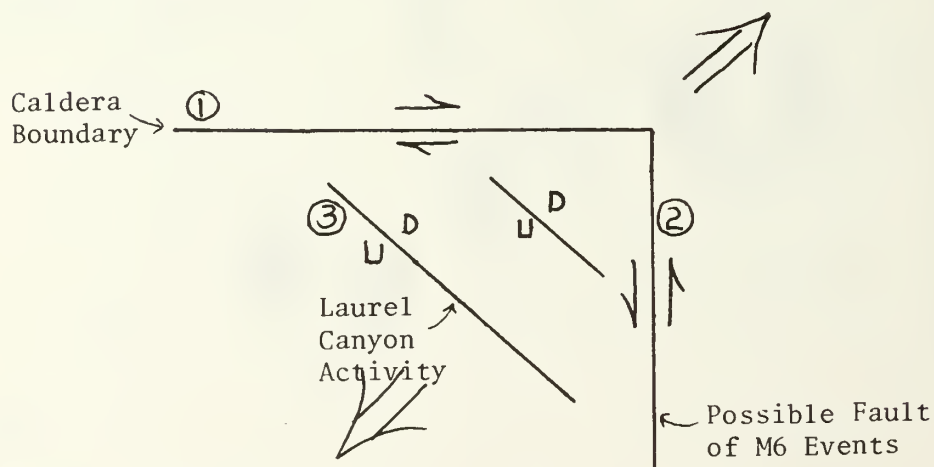
Figure 11

Two General Models of Faulting at Mammoth Lakes

A) Right-lateral strike-slip along offset in range front normal faults:



B) Conjugate strike-slip movements creating tensional faulting:



Circled numbers represent possible sequence of fault movements for Mammoth Lakes activity

from microearthquakes ($M < 3.0$) recorded in 1971 and 1973. They show dominantly strike-slip mechanisms, plus some normal mechanisms, all with tension axes generally ENE-WSW. Pitt and Steeples also obtained a composite focal mechanism for 4 events with hypocentral depths less than 10 km from their northern Owens Valley and Long Valley study area which showed strike-slip movement under N-S compressions and E-W tension. This is not shown on figure 10 because it is a composite for the entire area. Seventeen events, with depths greater than or equal to 10 km, showed no consistent first motion pattern.

MULTI-MOVEMENTS AND TECTONIC MODELS

Clearly, as indicated by the focal mechanism data for September and November, 1979, and by the epicentral distribution, the swarm activity in the Mammoth area for the 9 months preceding the M6 events occurred on right-lateral, strike-slip faults along the southern boundary of Long Valley caldera. The correspondence among the strike of the east-west plane of the focal mechanisms, the trend of the M4 epicenters in figure 6, and the orientation of the range front along the southern boundary of the caldera is good. The activity appears to have migrated westward and downward with time from near Casa Diablo to the vicinity of the mouth of Convict Creek Canyon before May, 1980. Further evidence for these M4 earthquake swarms being located near the southern boundary of the caldera and Casa Diablo is obtained from aftershock locations using local arrays operated by CDMG during September-October, and November, 1979 (figure 3a and b). These $M < 4$ aftershocks were located in the same area as events 2-11 in figure 6.

For the M6 sequence of May 1980, figure 4 shows the initial $M \geq 5$ activity proceeding along the southern margin of the caldera towards Mammoth Lakes (events 1-4). This suggests that the first two M6 earthquakes of the sequence were right-lateral, strike-slip along the

caldera margin. The third M6, on May 25th (event 5), initiated activity south of the caldera beneath the Sierra Nevada near Convict and Laurel Canyons. However, the remaining two $M \geq 5$ earthquakes on May 25th (events 6 and 7, figure 4) were again near the caldera boundary. The fourth M6 sequence was located south of the first and third ones. This suggests left-lateral, strike-slip motion for the M6 events south of the caldera based on their focal mechanisms and north-south alignment. However, there are no M5 earthquakes along the M6 trend, with the possible exception of event 7, figure 4. This lack of large aftershocks near the later M6 earthquakes is unusual. In fact, figure 5, showing $3.5 \leq M \leq 5$ aftershocks, does not indicate a vigorous aftershock zone associated with the southern two M6 events, only a diffuse pattern of aftershocks with a very tenuous north-south alignment along the trend suggested by the eastern three M6's. Thus, at present, it is not clear whether slip occurred on the left-lateral or right-lateral plane of the focal mechanisms for the third and fourth M6's of this sequence, but events 1-4 suggest that the first two M6's were the result of right-lateral movement along the caldera boundary faults.

The $M \geq 5$ activity in figure 4, near Laurel Canyon and near the juncture of the Hilton Creek fault and the southern boundary of the caldera, also are locations of $M \geq 3.5$ aftershocks in figure 5. The aftershock activity near Laurel Canyon appears particularly vigorous.

Two models of the faulting process for this sequence are suggested by the preliminary observations: 1) dominantly right-lateral, strike-slip movement on a series of en echelon E-W faults between left-stepping segments of the EFSN normal faults (figure 11a) and 2) a sequence of first right-lateral movement on an E-W fault and, then, left-lateral fault movement on a N-S fault, followed by normal dip-slip readjustments on secondary faults due to tension caused by the conjugate strike-slip movements (figure

11b). The preliminary results are consistent with either model.

The first model is suggested by the possibility of right-lateral movement, as well as some dip-slip movement, between left stepping normal fault segments, in a manner somewhat analogous to a transform fault between left-stepping ocean ridges. The southern boundary faults of Long Valley caldera are preexisting planes of weakness along which some of this movement could be accommodated. The diffuse aftershock zone south of the caldera boundary faults may be part of a complicated zone of right-lateral shear between two major segments of EFSN faults.

The second model allows for conjugate strike-slip faulting as a means of adjusting to NE-SW tension. The preliminary data clearly shows right-lateral, strike-slip movement along the southern boundary faults of Long Valley caldera from September 1979 through May 1980. The north-south alignment of the three eastern M6 earthquakes suggests conjugate left-lateral, strike-slip faulting on a N-S fault, some 5 km west of the Hilton Creek fault. The diffuse aftershock zone does not clearly delineate this zone, however. This conjugate movement would allow normal, dip-slip movements on one or several NW trending faults beneath the Laurel Canyon area. If the conjugate-slip pair moved because of regional NE-SW tension, secondary dip-slip movements might also occur along NW trending features to the north and east of the conjugate pair. Such a feature is the Hilton Creek fault near its juncture with the caldera southern boundary faults, both within and outside of the caldera. This interpretation seems the more likely, but preliminary focal mechanism results and the diffuse aftershock zone are not sufficiently constrained by the available data to preclude the right-lateral shear interpretation.

It may seem unusual to see NE-SW trending tension axes and strike-slip mechanisms in a tectonic environment where

the geologic evidence suggest faulting under east-west tension. Two mechanisms can be suggested to explain this observation. The first is a local modification of the regional stresses by the presence of a large caldera and/or a left step in the EFSN normal faults. The caldera, being a weaker "hole" in the crust, could allow a local rotation from a E-W tension axis to a NE-SW tension axis. It may also be possible that local rotation in regional stresses occur between the offset ends of range front faults. The 1973 mechanism of Steeples and Pitt (1976) indicates the possibility of local spatial rotation to NE-SW tension along the SW margin of the caldera.

The second mechanism to explain NE-SW tension and strike-slip movement is a temporal rotation of the regional stress field due to plate tectonic interactions that are currently not understood. That such a regional rotation may have occurred is suggested by comparing the 1971 focal mechanisms of Pitt and Steeples (1975) in figure 10 with those for 1978-1980 in figure 9. This comparison suggests rotation from ENE-WSW tension to NE-SW tension. Bufe *et al.* (1979) have observed temporal rotations in stress axes within The Geysers in northern California. Such a stress field rotation could allow a different set of faults to move while locking up faults less favorably oriented for movement.

In either case, the existence of strike-slip motion in a region of normal faulting is not unusual. Pitt and Steeples (1975) clearly demonstrated strike-slip faulting as well as some normal faulting, in the Long Valley-Northern Owens Valley area in the early 1970's. Also, recent work by Walter and Weaver (1980) for the Coso Range south of Owens Valley, shows the coexistence of normal and strike-slip faulting under the same E-W tensional regime.

MAGNITUDE-FREQUENCY DISTRIBUTION

Figure 12 shows magnitude-cumulative frequency plots for three periods: October 1978 - January 1979, February 1979 - April 1980, and May 1980. Magnitudes used in Figure 12 are Richter Magnitudes determined by CIT. b-values for each of these periods have been determined by least squares from the most linear segments at these plots. The resulting values for each period are:

October 1978 - January 1979:
b = 0.70 for 55 events

February 1979 - April 1980:
b = 0.89 for 132 events

May 1980: b = 0.89 for 471 events

The Mammoth M4 swarms and M6 sequence of 1979 and 1980 have b-values of about 0.7, which is normal for tectonic earthquakes in California. The October 1978 sequence appears to have an anomalously low b-value of 0.7. Using the distribution test for statistical significance, based on the number of samples (earthquakes) used to determine these b-values (Utsu, 1966), the b-value of the October 1978 sequence is different from the Mammoth earthquakes at almost the 90% confidence level. Thus, b-values suggest that the Mammoth area earthquakes are normal tectonic earthquakes for California, as opposed to volcanic earthquakes which have b-values usually greater than 1.

SUMMARY

Historically, the seismicity of the segment of the EFSN between Bishop and Long Valley has been high, with magnitude 5.0 earthquakes occurring at intervals of ten to twenty years. This suggests that the segment of the EFSN north of the 37° break is highly stressed. The series of earthquakes in May 1980 represents

the greatest seismic activity on the EFSN during the present century.

Detailed examination of the eleven $M \geq 5$ earthquakes of the May 1980 sequence, using CDMG local seismograph and accelerograph data and regional seismograph coverage, shows a complex migration of activity first from east to west along the southern boundary of Long Valley caldera, and then to the south on features west of the Hilton Creek fault. The three M6 earthquakes to the east occurred from the north near Convict Lake, and proceeded southward at 5 km intervals. The westernmost M6 earthquake occurred near Casa Diablo. Focal depths ranged from nine to sixteen kilometers. The major energy release, including all the M6 earthquakes of the sequence occurred on features west of the Hilton Creek fault, indicating that the Hilton Creek fault was not the causative fault for this activity, but only responded with secondary movements. This conclusion is supported by the distribution of $M \geq 3.5$ aftershocks recorded by a nine station local seismograph network between May 26 and June 8, 1980, these aftershocks being located west of the Hilton Creek fault.

The May 1980 activity was preceded by a series of M4 earthquake swarms starting in June 1979. Most of these M4 swarms occurred along the southern boundary of Long Valley caldera between Casa Diablo and Convict Creek. There was a general eastward and downward migration of these M4 swarms along the caldera boundary from Casa Diablo toward the eventual epicenter of the first M6 near Convict Lake. Although this activity served as a possible warning of future activity in the Mammoth area, there was no clear indication of whether or when the M6 events would occur.

Focal mechanisms for the three M6 earthquakes, and the M4 swarms that preceded them, are strike-slip, with east-west and north-south nodal planes very similar to those of the October 4,

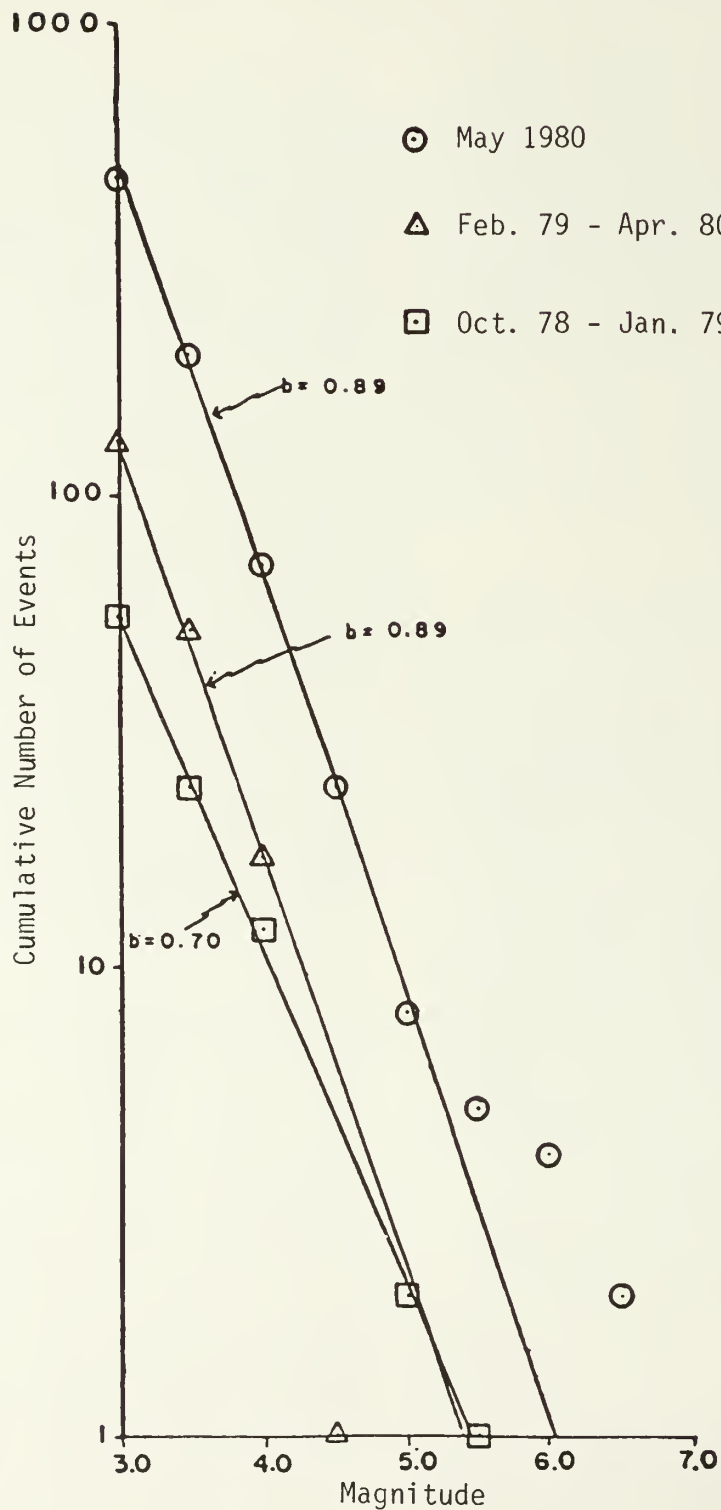


Figure 12. Magnitude-Frequency Diagram

1978 M5.8 earthquake south of Lake Crowley. The sense of motion is right-lateral on east-west faults and left-lateral on north-south faults. This implies NE-SW tension axes. The east-west distribution of activity and orientation of faults along the southern boundary of the caldera supports right-lateral movements on E-W faults for the M4 "fore-swarms" and the May 1980 events near the caldera boundary, including the first two M6's and the first several M5 earthquakes of the sequence. The diffuse nature of the aftershock distribution and ambiguities in the preliminary focal mechanism data do not allow, at this writing, a distinction for activity south of the caldera between a zone of right-lateral movement on E-W faults, and a zone of left-lateral movement on conjugate N-S faults.

Focal mechanisms from microearthquakes studied in Long Valley and northern Owens Valley during the early 1970's also show dominantly strike-slip movements, particularly from microearthquakes with focal depths less than 10 km. Some normal mechanisms were also observed. However, all mechanisms showed ENE-WSW tension axes, except one composite mechanism for a small swarm SW of Mammoth Lakes, which showed NE-SW tension. Many of these mechanisms were for the same area as the 1978-1980 mechanisms that have NE-SW tension axes. This suggests the possibility of a temporal regional stress field rotation between the early and late 1970's, although, local spatial variations in the regional stress field could explain some, but not all, of the observations.

b-values, for both the M4 swarms in 1979-80 and the May, 1980, M6 sequence are about 0.9. This value is normal for tectonic earthquakes in California and suggests that these earthquakes are not volcanic in nature. A b-value of 0.7 has been determined for the October, 1978, M5.8 sequence beneath Wheeler Crest.

Both the 1978 M5.8 and 1980 M6 earthquakes do not appear to be located on known normal EFSN faults. This, as well

as the focal mechanism data, indicates that this is a region of complex faulting and geologic interactions which should not be viewed in terms of simple extensional tectonics.

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APPENDIX I

This appendix lists locations for $M \geq 4$ Mammoth Lakes-Lake Crowley earthquakes for the period October, 1978, through May, 1980 (see Tables 1 and 2). Only $M \geq 5$ events are listed after May 24, 1980 (see Table 3). Information provided for each event is described below.

(1) EVENT identification number keyed to Figures 4, 6, and 8.

(2) DATE and ORIGIN time in Greenwich Civil Time (GCT): YEAR, MON (month), DY (day), HR (hour), MN (minute), and SEC (second).

(3) Epicenter in degrees and minutes of north latitude (LAT N) and west longitude (LONG W).

(4) DEPTH, epth of focus in kilometers.

(5) MAG, Estimated magnitude (M) of the earthquake. A letter B or P following a magnitude indicates a Richter magnitude determined by the University of California, Berkeley, Seismographic stations or by the California Institute of Technology's Seismological Laboratory, respectively.

(6) NO, number of phase arrivals used in locating earthquake.

(7) GAP, largest azimuthal separation in degrees between stations.

(8) DMIN, epicentral distance in kilometers to the nearest station.

(9) RMS, root-mean-square error of the time residuals: $RMS = (\sum R_i^2 / NO)^{1/2}$. R_i^2 is the observed seismic-wave arrival time minus the computed time at the i th station.

(10) ERH, standard error of the epicenter in kilometers: $ERH = (SDX^2 + SDY^2)^{1/2}$. SDX and SDY are the standard errors in latitude and longitude, respectively, of the epicenter.

(11) ERZ, standard error of the focal depth in kilometers.

(12) Q, solution quality of the hypocenter. This measure is intended to indicate the general stability of each solution.

<u>Q</u>	<u>Epicenter</u>	<u>Focal Depth</u>
A	excellent	good
B	good	fair
C	fair	poor
D	poor	poor

Q is based on both the nature of the station distribution with respect to the earthquake and the statistical measure of the solution. These two factors are each rated independently according to the following schemes.

Station Distribution

	<u>NO</u>	<u>GAP</u>	<u>DMIN</u>
A	≥ 6	≤ 90	$\leq$ DEPTH or 5 km
B	≥ 6	≤ 135	$\leq$ 2 X DEPTH or 10 km
C	≥ 6	≤ 180	$\leq$ 50 km
D	Others		

Statistical Measures

	<u>RMS (sec)</u>	<u>ERH (km)</u>	<u>ERZ (km)</u>
A	< 0.15	< 1.0	< 2.0
B	< 0.30	< 2.5	< 5.0
C	< 0.50	< 5.0	
D	Others		

Q is taken as the average of the ratings from the two schemes, i.e., an A and a C yield a B, and two B's yield a B. When the two ratings are only one level apart the lower one is used, i.e., an A and a B yield a B.

APPENDIX 1

TABLE 1

OCT 78 - MAY 79 EARTHQUAKES M≥4.0											
	DATE	ORIGIN	LAT N	LONG W	DEPTH	MAGNITUDE	NO GAP	DMIN	RMS	ERH	ERZ Q
1	781004	1642	48.53	37N31.77	118W39.65	19.65	5.8B 5.8P	14 73	7.6	0.29	2.1 3.5 B
2	781004	1659	4.21	37N31.49	118W40.01	17.94	4.4B 4.4P	5 111	109.7	0.02	4.5 11.0 D
3	781004	1731	31.11	37N32.00	118W40.21	18.23	4.2B 4.4P	6 111	57.0	0.06	1.7 3.7 C
4	781004	1739	3.15	37N32.38	118W40.35	19.03	5.1B 5.3P	6 110	56.5	0.04	1.0 1.7 C
5	781004	1746	46.63	37N32.95	118W40.78	5.56	4.2B 4.3P	5 110	110.2	0.12	5.6 49.4 D
6	781004	18 1	53.26	37N31.21	118W40.21	17.43	3.9B 4.1P	6 111	58.2	0.03	0.9 1.9 C
7	781004	1822	41.56	37N30.23	118W40.04	16.91	4.4B 4.4P	6 112	59.6	0.08	2.4 5.4 D
8	781005	117	47.19	37N31.03	118W40.42	11.78	4.6B 4.4P	6 111	58.6	0.04	1.1 9.4 D
9	781005	641	29.92	37N29.77	118W40.02	18.37	4.4B 4.4P	5 176	60.3	0.02	6.2 7.6 D
10	781026	19 0	41.11	37N30.60	118W41.12	11.75	4.0B	6 111	59.9	0.07	1.5 11.3 D
11	790119	1810	41.62	37N34.02	118W39.74	7.99	4.0B 4.3P	5 110	112.6	0.01	3.3 26.1 D
12	790124	2114	27.27	37N31.88	118W35.85	16.35	4.4B 4.4P	13 85	11.4	0.17	1.1 1.6 B

APPENDIX 1

TABLE 2

JUNE 79 - MAY 80 EARTHQUAKES $M \geq 4.0$ (FORESWARMS)

	DATE	ORIGIN	LAT N	LONG W	DEPTH	MAGNITUDE	NO GAP	DMIN	RMS	ERH	ERZ	Q
1	790616	2244 59.31	37N35.50	118W56.74	5.11	3.6B 4.3P	9 99	69.6	0.09	1.1	2.3	C
2	790907	943 48.45	37N38.17	118W55.50	4.59	4.2B 4.4P	8 98	65.3	0.12	1.6	3.6	C
3	790924	13 5 4.57	37N37.60	118W54.82	3.18	4.1B 4.3P	7 98	65.1	0.09	1.5	3.4	C
4	790924	1426 19.85	37N38.48	118W55.55	5.22	3.6B 4.0P	8 98	65.1	0.07	0.8	1.9	C
5	791109	1012 54.88	37N37.06	118W52.98	4.33	3.9B 4.0P	10 100	63.4	0.12	1.2	2.8	C
6	791109	1746 57.97	37N37.34	118W52.76	5.50	3.8B 4.1P	8 100	62.9	0.05	0.8	1.3	C
7	791109	1754 14.65	37N38.21	118W54.57	6.71	4.1B 4.4P	4 114	100.7	0.00	11.5	71.0	D
8	791110	945 8.73	37N37.68	118W53.14	5.22	3.9B 4.2P	7 99	63.0	0.06	0.9	1.9	C
9	791120	1723 58.74	37N37.26	118W52.59	5.82	4.2B 4.2P	10 100	2.3	0.11	1.0	1.2	B
10	791206	1932 38.65	37N36.94	118W51.69	6.57	4.2B 4.3P	12 77	2.7	0.15	1.2	1.1	B
11	791208	2138 52.18	37N36.80	118W53.45	4.80	4.3B 4.3P	13 84	2.8	0.14	1.3	1.1	B
12	791226	8 9 4.36	37N33.29	118W48.03	10.02	4.0B 4.1P	9 105	7.1	0.05	0.7	0.8	B
13	800114	2351 54.69	37N37.51	118W48.31	9.02	4.0B 4.2P	7 146	7.8	0.03	0.9	0.7	C
14	800320	11 5 42.38	37N38.63	118W54.61	8.43	3.8B 4.0P	8 98	63.8	0.15	2.1	5.9	D
15	800320	1642 48.27	37N37.00	118W53.77	4.49	3.7B 4.0P	10 116	2.4	0.13	1.6	1.4	B
16	800327	226 4.45	37N38.10	118W53.80	7.92	4.3B 4.5P	11 99	0.6	0.14	1.4	1.2	B
17	800514	8 2 32.11	37N38.38	118W50.30	8.90	4.1B 4.1P	13 95	2.9	0.20	1.7	1.1	B
18	800517	0 1 13.97	37N37.78	118W50.19	5.50	4.3B 4.5P	11 92	1.8	0.12	1.3	1.4	B
19	800518	1247 29.90	37N37.77	118W53.14	7.53	4.0B 4.1P	9 99	1.1	0.08	1.4	0.9	B
20	800525	449 34.67	37N37.90	118W53.08	7.30	4.0P	9 99	9.0	0.13	2.0	1.5	B

APPENDIX 1

TABLE 3

	DATE	ORIGIN	LAT N	LONG W	DEPTH	MAGNITUDE	NO	GAP	DMIN	RMS	ERH	ERZ	Q
1	800525	1633	44.77	37N36.54	118W50.81	8.87	6.1B	6.5P	19	57	1.5	0.15	0.9 B
2	800525	1635	53.73	37N36.80	118W52.57	7.98		5.0P	5	191	4.0	0.03	36.2 11.9 D
3	800525	1649	27.04	37N37.65	118W55.64	13.79	6.0B	6.0P	10	93	3.5	0.13	1.5 1.6 B
4	800525	17 6	23.70	37N36.45	118W53.24	5.08	4.7B	4.9P	5	145	5.1	0.23	3.8 6.8 D
5	800525	1944	51.42	37N33.64	118W49.86	16.38	6.1B	6.7P	13	62	5.9	0.16	1.2 1.6 B
6	800525	2035	48.18	37N37.50	118W51.55	2.28	5.7B	5.5P	10	76	2.8	0.12	1.1 1.6 B
7	800525	2059	23.07	37N35.72	118W50.03	9.53	5.0P	4.9B	11	58	2.1	0.13	1.1 1.3 B
8	800526	1224	25.48	37N34.57	118W54.06	6.88	5.1B	5.2P	16	71	6.9	0.08	0.5 0.7 B
9	800526	1857	56.11	37N32.60	118W53.29	4.65	5.7B	4.9P	13	97	9.4	0.11	0.8 1.6 B
10	800527	1450	57.17	37N30.34	118W49.57	14.18	6.2B	6.3P	23	84	5.0	0.18	1.0 1.4 B
11	800527	19 1	8.29	37N35.72	118W47.48	5.91	4.8B	5.0P	17	62	4.0	0.14	0.8 1.0 B

MAY 1980 EARTHQUAKES WITH $M \geq 5.0$

APPENDIX II

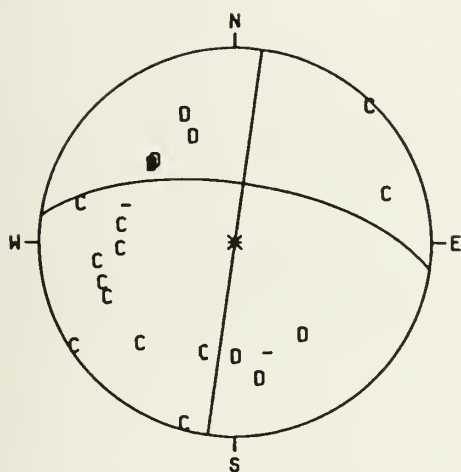
This appendix contains detailed plots of the 6 focal mechanisms presented in figure 9 and discussed in the text. The strikes and dips of the two fault planes of each mechanism are listed below each plot. All focal mechanisms are lower hemisphere, equal area projections with C and + representing compressional first motions, and D and - representing dilatational first motions. First motions represented by + or - are weak or emergent or questionable first breaks. The table preceding the focal mechanism plots lists the events on whose data each plot is based. The table is arranged by mechanism and identified by a letter. Summary information and quality is provided for each event. See Appendix I for an explanation of summary information entries and the definition of quality Q.

APPENDIX II

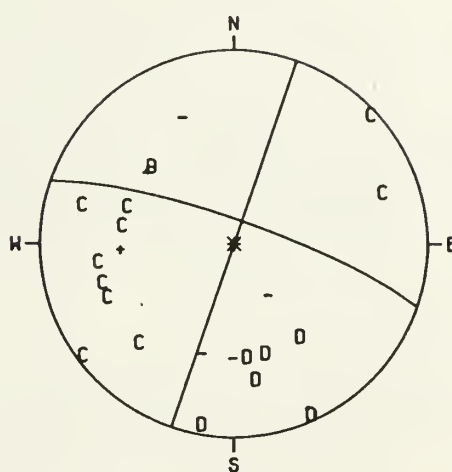
TABLE OF EVENTS CONTRIBUTING TO EACH FOCAL MECHANISM

DATE	ORIGIN	LAT N	LONG W	DEPTH	MAGNITUDE	NO GAP	DMIN	RMS	ERH	ERZ	Q
MECHANISM A:											
790907	943	48.46	37N38.15	118W55.49	4.70	4.4P	4.2B	9	98	49.0	0.11 1.3 2.8 C
MECHANISM B:											
791120	1723	58.75	37N37.22	118W52.59	5.84	4.2P	4.2B	11	100	2.4	0.11 0.9 1.2 B
MECHANISM C:											
800525	1633	44.77	37N36.54	118W50.81	8.85	6.5P	6.1B	19	57	1.5	0.15 0.9 0.9 B
MECHANISM D:											
800525	1649	27.04	37N37.65	118W55.64	13.79	6.0P	6.0B	10	93	3.5	0.13 1.5 1.6 B
MECHANISM E:											
800525	1944	51.43	37N33.76	118W50.29	15.30	6.7P	6.1B	15	60	5.7	0.15 1.0 1.5 B
MECHANISM F:											
800527	1450	57.17	37N30.34	118W49.56	14.15	6.3P	6.2B	23	84	5.0	0.18 1.0 1.4 B

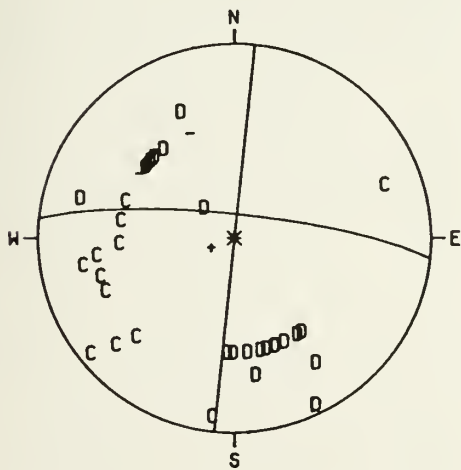
APPENDIX II



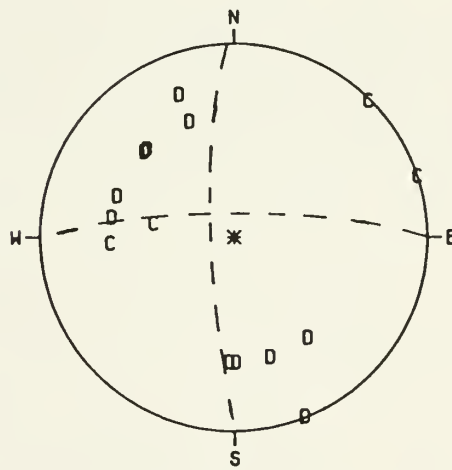
A: N 8E, 90 & N82W, 65N



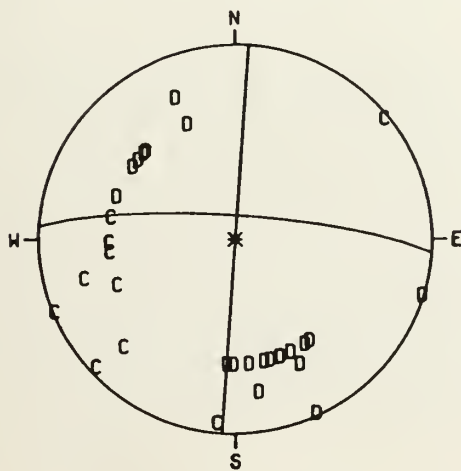
B: N19E, 90 & N71W, 80N



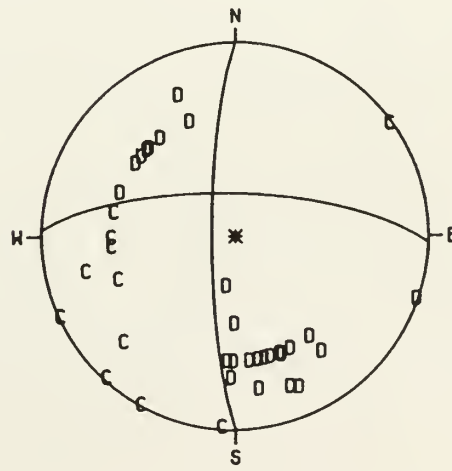
C: N 6E, 90 & N84W, 80N



D: N 2W, 80W & N90E, 80N



E: N 4E, 90 & N86W, 80N



F: N 0W, 80W & N88W, 72N

APPENDIX III

This appendix contains interesting observations associated with the earthquakes in the Mammoth Lakes-Lake Crowley area.

Earthquake Sounds

During the course of the Mammoth activity in May and June, 1980, and also in November 1979, many small earthquakes ($M < 3$) were felt and heard, or many times just heard by the authors and members of the CDMG field parties. Similar sounds were heard at station CSMR (figure 3d) in October 1978. This was in addition to feeling the larger earthquakes ($M \geq 3$) particularly the M_6 event on May 27th. Booming sounds were particularly audible in McGee Creek Canyon both in November 1979, and May 1980. These sounds were particularly noticeable while changing records at our Upper McGee Creek seismograph station. Distinctly audible booms were associated with the onset of small microearthquakes on the smoked drum record. Larger (louder) booms were accompanied with perceivable ground motion, larger amplitude earthquakes on the smoked drum record and sometimes loose rock rattling down debris chutes and slides. Similar distinct booms of various intensities were noted at the mouth of McGee Canyon within a few hundred yards of the Hilton Creek fault on the evening of May 25th, but most were unaccompanied by felt ground motion.

Similar earthquake sounds have been reported by Hill *et al.* (1976) for a swarm in Imperial Valley, California, and by Stierman (1980) for the 1979 Homestead Valley sequence. Based on our experiences with audible booms associated with aftershocks of the 1979 Imperial Valley

sequence, the Mammoth aftershocks were much more distinct when heard in McGee Creek Canyon. The description by Stierman of the booms sounding like a single note from a low pitched timpani best describes the sounds observed at McGee Creek.

Hot Spring Activity

Changes in hot spring activity at Hot Creek were noticed at the time of the October 4, 1978 and May 24, 1980 earthquakes. A 40-foot geyser of hot water developed shortly after the October 4, 1978, $M_{5.8}$ earthquake and subsided over a day or two (Debbie Massingwale, USF, oral communication, 1978). Forest Service rangers in charge of the recreational site closed the hot pools to protect the public. During the M_4 swarms from June 1979 through mid-May, 1980, no particular change in hot spring activity was noticed by the Forest Service. Associated with the May 25 M_6 earthquakes was an increase in water temperature which forced the closing of the Hot Creek area temporarily. According to Forest Service personnel, a new spring started developing at the Hot Creek site the day before the May 25 events (Robert Nason, oral communication).

Most of these observed changes could be explained by shaking effects on the water plumbing of the hot springs. As reported by local newspapers, the May 25th event also increased turbidity at a well at Casa Diablo, at the Mammoth fish hatchery, and in Hot Creek above the hot springs area. The only report that may have indicated precursory changes at Hot Creek was the development of a new spring one day prior to the May 25 sequence.

THE 1980 MAMMOTH LAKES EARTHQUAKE SEQUENCE

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ABSTRACT

On May 25, 1980, at 1633 UTC, a large earthquake (M_L 6.1) occurred in the vicinity of Mammoth Lakes, California (37.6°N by 118.8°W). By August 1, 1980, a sequence of approximately 600 earthquakes of magnitude 3.0 or larger had occurred in the region. A plot of the cumulative number of earthquakes shows that there is an excess of earthquakes over magnitude 5.0 (nine in all) and that the b-value for the sequence is (0.94 ± 0.038) . The sequence occurrence rate follows an Omori relation with $n(t) \propto t^{-0.82}$.

The local magnitude (M_L) of the earthquakes were estimated using up to ten Wood-Anderson seismograms, and the four largest earthquakes in the sequence were assigned local magnitudes of 6.1, 6.0, 6.1, and 6.2.

The seismic moments of the four largest earthquakes, 5.1, 3.7, 3.0, and 5.0 ($\times 10^{24}$ dyne-cm) were estimated from broadband displacement seismograms recorded at Jamestown (approximately 150 km west of the epicenters).

INTRODUCTION

Much of central and eastern California and southwestern Nevada was shaken relatively strongly by a large earthquake (M_L 6.1) on the morning of May 25, 1980 (9:33 a.m. PDT). This earthquake was the beginning of a sequence of earthquakes which included four large earthquakes (M_L 's 6.1, 6.0, 6.1 and 6.2) and approximately 300 earthquakes of M_L 3.0 or larger during the following two days. The large earthquakes were generally reported felt over a radius of approximately 250km, and some damage to structures occurred in the town of Mammoth Lakes, California.

The epicentral region ($37^\circ 33'\text{N}$ by $118^\circ 49'\text{W}$) is centered approximately 15km southeast of Mammoth Lakes, 230km south of Reno, and 320km east of San Francisco.

This report is concerned with three topics of general interest: the estimation of local magnitude (M_L); the estimation of seismic moment (M_0); and a statistical analysis of the sequence.

SEQUENCE CHARACTERISTICS

The Mammoth Lakes sequence through August 1, 1980, consisted of 605 earthquakes with a local magnitude (M_L) of 3.0 or larger. Four earthquakes registered M_L 6.0 or larger, and the largest one (M_L 6.2) occurred approximately two days after the beginning of the sequence (see Table 1).

The rate of seismicity as a function of time, $n(t)$, is plotted in Figure 1. Each point in the figure is estimated from 20 consecutive $M_L \geq 3.0$ earthquakes, and the error bars represent one standard error. The rate of occurrence, $n(t)$, may be fitted by Omori's relation: $n(t) = A/(t+c)^p$, and the least-squares solution gave $p = 0.82 \pm 0.034$ and $A = 39.6 \pm 6.0$. The rate $n(t)$ is 46 ± 7 earthquakes per hour ($M_L \geq 3.0$) for the first hour of the sequence. For comparison, 46 events per hour is approximately 1.4×10^5 times the background rate of $(3.4 \pm 0.68) \times 10^{-4}$ events per hour for the decade 1969-1978, and approximately 2700 times the background rate of $(1.7 \pm 0.65) \times 10^{-2}$ events per hour for the twelve months preceding the sequence. If the decrease in $n(t)$ continues to follow the trend in Figure 1, it will take (1.4 ± 0.56) years to decay to the background rate for the year prior to the sequence, and (980 ± 208) earthquakes ($M_L \geq 3.0$) will have occurred in the sequence. The estimated time required to decay to the

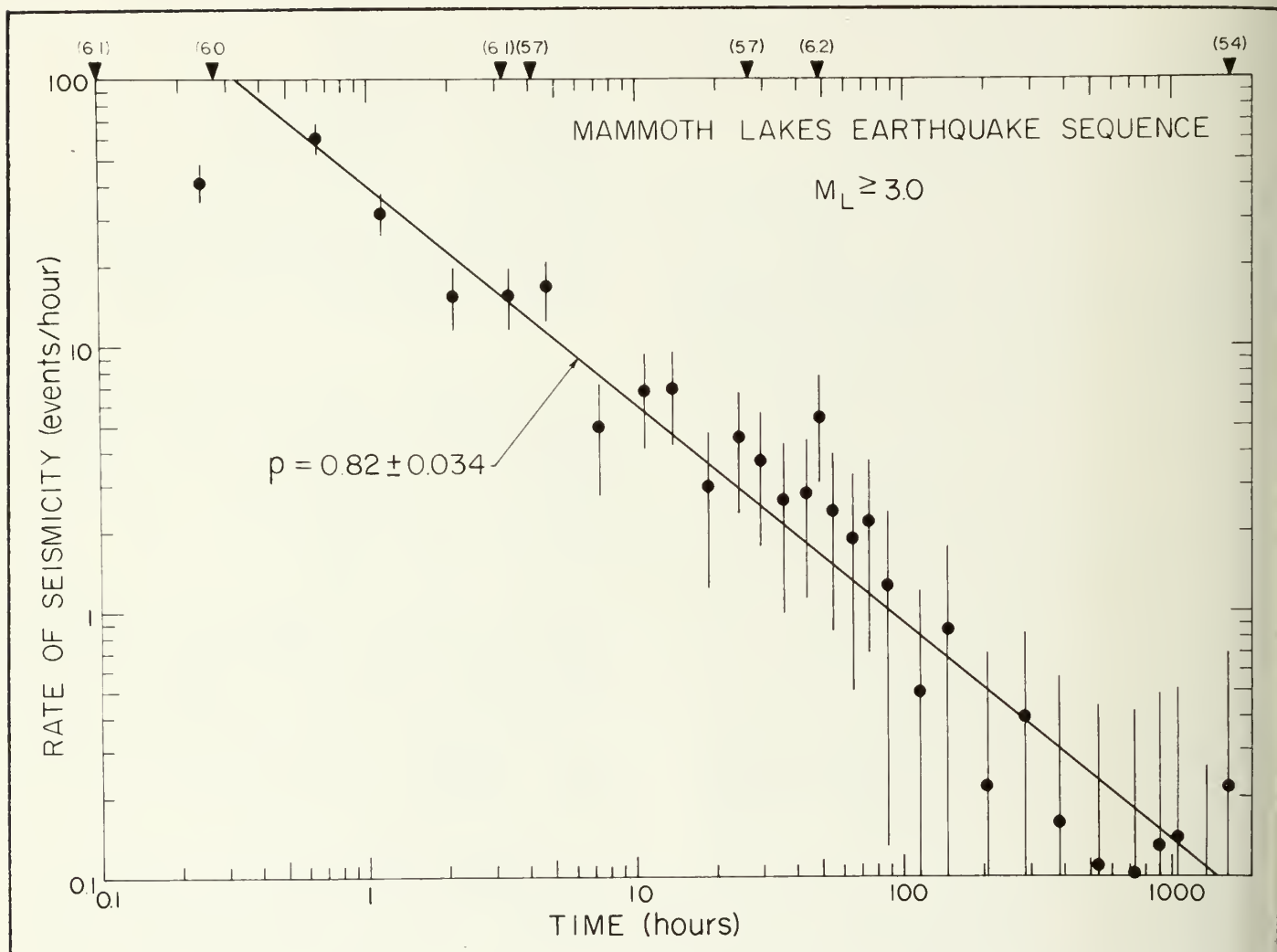


Figure 1

background rate for the past decade is (170 ± 105) years.

The cumulative number of earthquakes ($M_L \geq 3.0$) through August 1, 1980, is plotted in Figure 2. The equation $\log(N) = a - bM_L$ (N is the cumulative number of earthquakes of magnitude greater than or equal to M_L) was fitted by maximum likelihood and yielded $b = (0.94 \pm 0.038)$. Note that earthquakes above $M_L 5.1$ trend above the line (in Figure 2), suggesting that there is an excess of larger magnitude earthquakes in the sequence.

LOCAL MAGNITUDES

Local magnitude estimates (M_L) listed in Table 1 are from the maximum trace amplitudes measured on the Wood-Anderson seis-

mograms recorded at Arcata (ARC) ($\Delta \approx 588$ km), Berkeley (BKS) ($\Delta \approx 307$ km), Mt. Hamilton (MHC) ($\Delta \approx 254$ km), Mineral (MIN) ($\Delta \approx 395$ km), and on the 100X torsion seismograms recorded at Berkeley (BRK) ($\Delta \approx 309$ km). When computing the local magnitude for each earthquake (listed in Table 1), the instrumental magnitude adjustments (s) were estimated and removed. Referring to Table 1, the magnitude adjustment (s) for each instrument was estimated from the average of the magnitude residuals for all earthquakes recorded by the instrument (the M_L residual is equal to the M_L estimate from a given instrument minus the average of the M_L estimates from all instruments which recorded the earthquake). There are 27 earthquakes listed in Table 1, which is considered complete for M_L greater than or equal to 4.5.

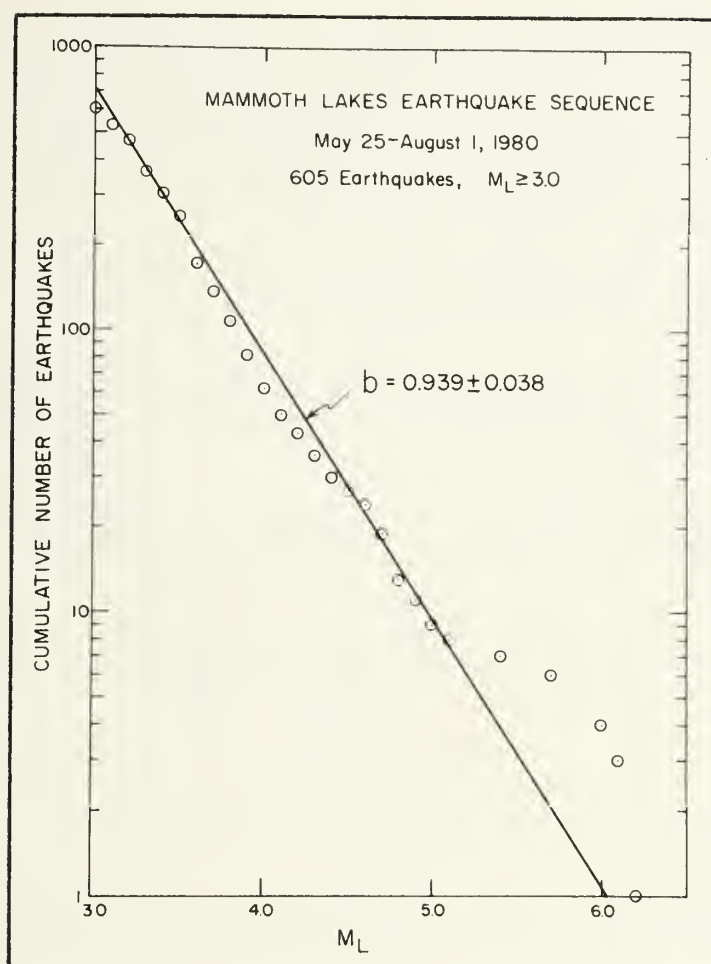


Figure 2

SEISMIC MOMENTS

The seismic moments (M_0) of the four largest earthquakes in the sequence (see Table 2) were estimated from the broadband displacement seismograms (shown in Figure 3) recorded by the vertical seismograph at Jamestown (JAS) using the far-field formulation: $M_0 = 4\pi\rho\beta^3r\Omega_0$. The Jamestown seismograph is flat in displacement response from 0.1sec to 40sec, and Ω_0 is estimated from the asymptotic low-frequency level of the spectra shown in Figure 3. A 51.2 second sample of the whole seismogram is transformed to obtain the Fourier spectrum.

The first large earthquake (May 25, at 1333UTC) generated more low frequency energy than did the other three earthquakes as indicated by the seismograms and their corresponding spectra as shown in Figure

3. The low-frequency characteristic of the first large earthquake is particularly evident on the Berkeley (BKS) ultra-long-period seismograms shown in Figure 4. Note the size of the long period pulse in the P-wave train on the seismogram for the first earthquake.

ACKNOWLEDGMENTS

The authors acknowledge K.L. McLaughlin for digitizing the seismograms and computing Fourier spectra, and M.R. McKenzie for drafting the figures.

This paper was reviewed by Professor T.V. McEvilly.

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TABLE 1. MAMMOTH LAKES EARTHQUAKES $M_L \geq 4.5$

Date 1980	Time (UTC)	BRK		BKS		MHC		MIN		ARC		$M_L \pm \sigma_{M_L}$	n
		N	E	N	E	N	E	N	E	N	E		
May 25	1633	5.99	5.95	5.99	5.97	5.86	5.30	6.12	6.44	6.43	6.26	6.09±.19	10
	1649	5.88	5.75	-	-	5.79	5.74	6.04	6.20	6.31	6.18	5.99±.23	8
	1706			4.51	4.46	4.68	4.61	4.55	4.89	4.77	4.70	4.65±.12	8
	1708			4.47	4.64	4.90	4.78	4.74	5.14	4.40	4.40	4.68±.15	8
	1748			4.51	4.51	4.72	4.60	4.67	4.87	4.40	4.40	4.59±.07	8
	1834			4.62	4.52	4.73	4.64	4.59	4.67	4.46	-	4.59±.13	7
	1904			4.42	4.42	4.66	4.56	4.48	4.72	-	-	4.52±.08	6
	1944			6.10	6.11	5.86	5.81	6.10	6.45	6.19	6.09	6.09±.17	8
	2035			5.59	5.55	5.56	5.42	5.81	5.99	5.77	5.68	5.67±.13	8
	2059			5.03	5.00	5.24	5.07	4.95	5.25	4.82	4.62	5.00±.15	8
26	0119			4.54	4.55	4.38	4.38	4.70	5.01	4.70	4.40	4.58±.14	8
	0556			4.55	4.49	4.78	4.66	4.74	5.13	4.52	4.46	4.67±.09	8
	1020			4.47	4.34	4.52	4.48	4.59	4.76	4.52	-	4.51±.06	7
	1224			4.86	5.00	5.29	5.12	5.28	5.54	4.92	4.92	5.12±.12	8
	1620	5.52	5.56	4.71	4.75	5.04	4.84	4.76	5.12	4.87	4.62	4.84±.09	8
	1857			5.54	5.63	5.87	5.59	5.64	5.95	5.51	5.68	5.69±.12	10
	1924			4.66	4.62	5.02	4.70	4.87	5.07	4.40	-	4.74±.15	7
	1450	6.24	6.06	6.25	6.10	5.93	5.93	6.32	6.45	6.44	6.31	6.23±.19	10
	1901			4.74	4.71	4.89	4.63	5.16	5.25	4.62	4.40	4.80±.18	8
	0516			4.77	4.90	5.14	4.90	4.82	5.17	4.77	4.62	4.89±.11	8
31	0548			4.54	4.38	4.74	4.68	4.39	4.74	4.52	4.52	4.56±.14	8
	0058			4.29	4.34	4.58	4.52	4.62	4.93	-	-	4.52±.09	6
	1516			4.75	4.74	4.94	4.85	5.04	5.24	4.82	4.52	4.86±.10	8
Jun 01	0647			4.40	4.44	4.82	4.57	-	5.02	4.40	-	4.59±.12	6
	0440			4.47	4.69	4.75	4.52	4.74	5.07	4.62	4.52	4.67±.07	8
Aug 01	1638	5.36	5.26	5.28	5.38	5.74	5.48	5.32	5.76	5.35	5.12	5.43±.12	10
	1648			4.65	4.63	4.71	4.57	4.62	4.92	4.62	-	4.66±.06	7
s		-0.68	-1.50	-0.98	-0.92	.070	-0.67	.039	.315	-0.41	-1.29		
σ_s		± 0.67	± 0.55	± 0.84	± 0.70	± 0.171	± 0.122	± 0.111	± 0.099	± 0.179	± 0.182		
n		5	5	26	26	27	27	26	27	25	20		

JAS DISPLACEMENT SEISMOGRAMS AND SPECTRA

Mammoth Lakes Earthquake Sequence

May 1980

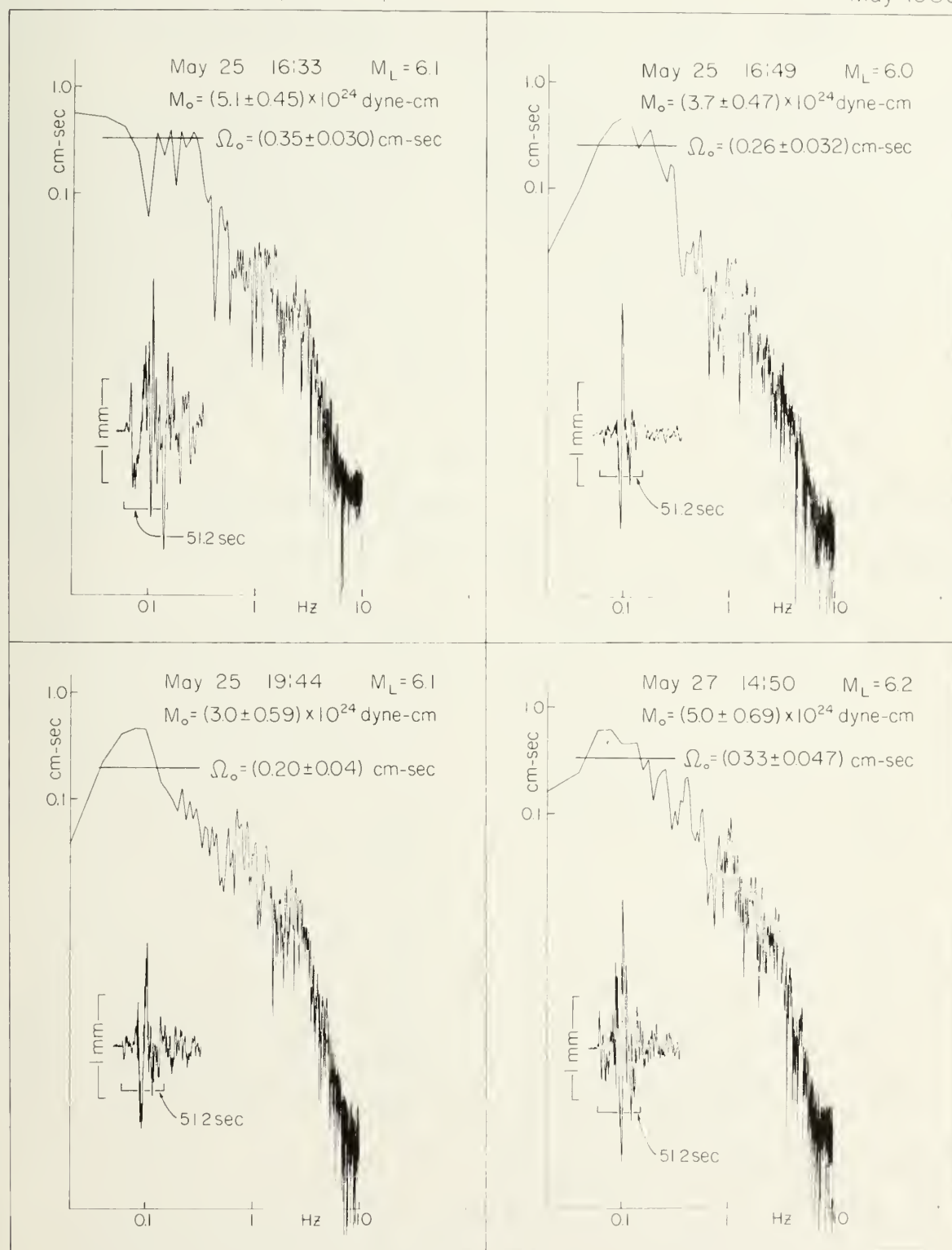


Figure 3

TABLE 2. SEISMIC MOMENTS

Date (1980)	Time (UTC)	Ω_0 (cm-sec)	r (km)	M_0 ($\times 10^{24}$ dyne-cm)
May 25	1633	0.35 ± 0.030	146	5.1 ± 0.45
	1649	0.26 ± 0.032	143	3.7 ± 0.47
	1944	0.20 ± 0.040	149	3.0 ± 0.59
May 27	1450	0.33 ± 0.047	153	5.0 ± 0.69

Mammoth Lakes Earthquake Sequence
May 1980

BROADBAND DISPLACEMENT SEISMOGRAMS

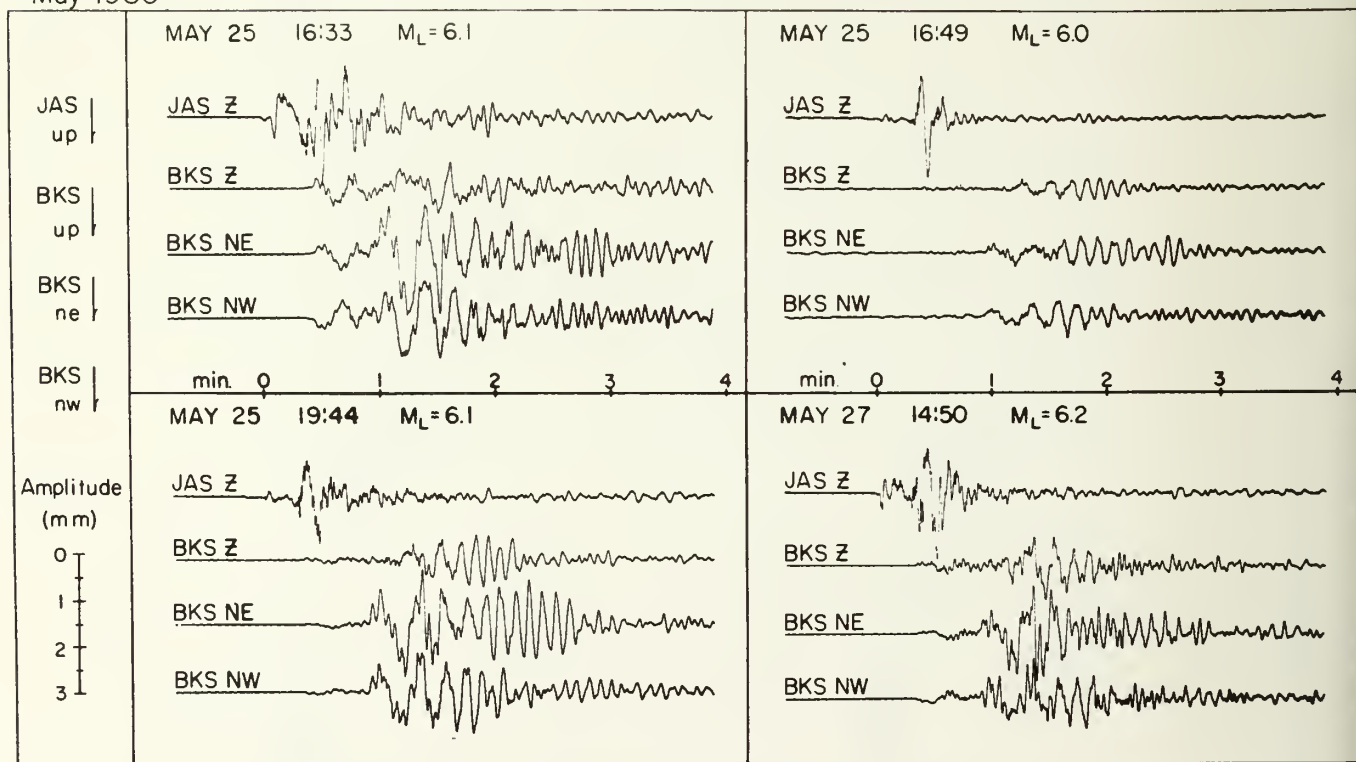


Figure 4

PLANNED ZONING OF ACTIVE FAULTS ASSOCIATED WITH

THE MAMMOTH LAKES EARTHQUAKES OF MAY, 1980

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Following the May 1980 Mammoth Lakes earthquakes, ground rupture due to faulting occurred near Mammoth Lakes in a broad zone 20 km long. Under California law, the State Geologist is required to establish regulatory zones for active faults that might constitute a hazard to structures as a result of surface fault-rupture. Such zones--known as Special Studies Zones--are planned for the Mammoth Lakes area as soon as practicable.

BACKGROUND

The Alquist-Priolo Special Studies Zones Act of 1972 (Public Resources Code, Div. 2, Chap. 7.5) requires the State Geologist (Chief, California Division of Mines and Geology) to "delineate... appropriately wide special studies zones to encompass" traces of the San Andreas, Calaveras, Hayward, and San Jacinto faults, and such other faults that are deemed sufficiently active and well-defined as to constitute a potential hazard to structures from surface faulting and fault creep." The State law specifically prohibits structures for human occupancy from being constructed across the trace of an active fault. An active fault is one that has been active during Holocene time, or approximately the last 11,000 years. Implementation of the Alquist-Priolo Act is largely by the cities and counties under guidelines provided by the State Mining and Geology Board. Local jurisdictions affected by the regulatory zones must require a geologic investigation (special study) for each "project" development proposed.

The Special Studies Zones of the California Division of Mines and Geology (DMG) are drawn on topographic base maps of the U.S. Geological Survey at a scale of 1:24,000 (one inch equals 2000 feet).

Recently established zones are about 300 m (1000 feet) wide for individual fault traces, but are wider where there are multiple fault traces. As of January 1, 1980, 288 zone maps had been established for those faults shown on Figure 1. The regulatory zones affect 69 cities and 24 counties. Additional data on the CDMG fault zoning program and details of the Alquist-Priolo Act are provided by Hart (1980).

FAULT RUPTURE OF MAY 1980

As detailed by Bryant and others (1980) and by Taylor and Bryant (accompanying paper), ground rupture from faulting occurred east of Mammoth Lakes along the Hilton Creek fault and its northwestern branches in a zone at least 20 km long by 9 km wide. Very minor extensional cracking also occurred along the "Earthquake Fault", 3 km west of Mammoth Lakes (town). This fault is a north-trending fissure--one of several such features associated with the north-trending Inyo Craters volcanic chain. Ground rupture along the Hilton Creek fault zone generally occurred as linear zones of discontinuous open cracks, commonly with downhill movement along pre-existing fault scarps. The sense of surface displacement was that of normal (dip-slip) faulting (down to the east) along the Hilton Creek fault and extensional opening and complex normal faulting in the western part of the Long Valley Caldera. The dip-slip displacement and horizontal extension observed are typical of normal faulting along steeply-dipping (but generally non-vertical) faults. The surface deformation is a blend of differential settlement and slight horizontal extension. The style of faulting is exemplified by Bailey (1974). The amount of measurable dip-slip displacement at individual cracks

generally was less than 5-6 cm. However, larger displacement may have been masked by soft soils or distributed across zones of multiple cracks. On the other hand, intense shaking apparently enhanced the cracking and downhill movement along some of the faults. The effect of this would be to exaggerate the amount of dip-slip or extension attributed to faulting. Work is still underway by CDMG staff to learn more of the extent and magnitude of faulting at Mammoth Lakes. Although the principal faults probably have been mapped, a complete knowledge of the fault rupture probably will never be obtained.

It is important to note that at the time of the earthquakes, most of the higher ground was partly covered with snow and could not be checked effectively. Moreover, frequent rains and animal activity tended to degrade the cracks in the soft soil (colluvium, talus, pumice) before the fault-associated cracks could be mapped. The lack of a good quality topographic map (Mount Morrison 15-minute quadrangle, 1953) further limited the accurate locations of faults. So far, it has not been possible to relate the ground rupture features with specific earthquakes. Presumably some of the surface faulting was directly associated with the three principal events of May 25 and 27 and some probably resulted from the larger after-shocks. Conceivably, some of the surface faulting may have preceded the principal events. Several fault localities also were checked for afterslip June 26-27, but none was noted. However, afterslip generally occurs after ground rupture events on normal faults and may continue for months or even years as the ground adjusts to gravity settlement. Displacement may be somewhat distributive over wide zones and may not be noticed except where roads or other structures are present.

The pattern of faulting near Mammoth Lakes was extremely complex, with numerous branching and subsidiary traces (see paper by Taylor and Bryant, this volume). Fortunately, most of the more important zones of cracking and ground failure

coincided with known faults (Bailey and Koeppen, 1977) which are readily recognizable on aerial photographs. Most of the linear crack zones not associated with fault scarps did not appear to have much displacement or length.

It could be argued that most of the linear ground failure was due to landsliding along zones of weakness (sheared and altered rocks) on steep slopes (scarps). Certainly, the loose soil and colluvium did move downslope on the steeper scarps. As much as one meter of downhill movement was observed locally and crack zones sometimes appeared both high and low on the scarp slope. However, the linearity and general coincidence of ground failure with the lower part of the fault scarps is remarkable and suggests some fault displacement at or very close to the ground surface. A structure built across a fault scarp along which ground failure occurs, of course, may not be able to distinguish between faulting or landsliding triggered by faulting.

Another phenomenon associated with the active fault traces was rock falls. In some cases, the rocky scarps seem to dis-aggregate--apparently from shaking--giving rise to local rock falls and talus aprons. A number of large boulders also moved downslope a considerable distance, leaving a trail of broken trees, craters and trenches as evidence of their paths. It is not known to what extent the faulting contributed to these rock falls, but slight fault movement could have caused slope instability and thereby enhance the shaking effects.

Finally, a certain amount of surface warping probably occurred in association with faulting, but the extent of this was not readily observable. Observation of other normal fault-rupture events indicates that extreme tilting is confined to a narrow zone along the zone of rupture, particularly on the adjacent down-thrown block.

ZONE PROCEDURES AND CRITERIA

Under the CDMG 10-year fault evaluation program (Hart, 1980), faults of the Sierra Nevada, including Mono County, were scheduled for evaluation in 1982 to determine which faults were "sufficiently active and well-defined" to warrant zoning. Specifically, those faults considered to have been active during Holocene time ("sufficiently active") and which are identifiable surface features ("well-defined") would have been zoned under the Alquist-Priolo Act. The Hilton Creek fault and some of its more obvious northwestern branches are known to offset Holocene geologic units (Bailey, 1974; Bailey and Koeppen, 1977) and clearly meet the criteria for zoning. The 1980 ground-rupture near Mammoth Lakes largely coincided with the known recent faults and support the concept that recently active faults are apt to be reactivated in the future.

In some ways, the 1980 events have simplified the job of identifying many of the active faults in the Mammoth Lakes area. Because the Mammoth Lakes area is under current development, the CDMG plans to establish Special Studies Zones around the active faults of the area at the earliest convenient time. The procedure will be to issue Preliminary Review Maps of the Special Studies Zones (probably in July 1, 1981) followed by Official Maps 6 months later. Various government agencies and the public will have an opportunity to review and comment on the Preliminary Maps prior to the release of the Official Maps. It is not possible to identify all of the faults to be zoned at this time nor to provide precise locations of zone boundaries. Specific recommendations for zoning will be made only after field and aerial photo interpretations are completed. Zoning will be based both on ground rupture and on the principal fault features (mainly scarps) that can be observed. An in-house Fault Evaluation Report will be prepared by the CDMG recommending zoning actions prior to the issuance of Preliminary Review Maps.

LIMITATIONS

Because ground rupture associated with the May 1980 events is so complex and the cracks formed in the soil are so ephemeral, it is not reasonable to expect that all of the active faults in the Mammoth Lakes area will be identified. Therefore, it is requested that additional documented evidence for faulting, other than that presented in the accompanying paper by Taylor and Bryant, be submitted to this writer (Room 1009, Ferry Bldg., San Francisco 94111) for consideration in zoning. Such information will be appreciated and will be used in making the final zoning decisions. Those persons providing information should keep in mind that ground failure also resulted from seismic shaking away from the active faults--particularly along margins of lakes, streams and valleys.

SUMMARY

1. Surface fault rupture occurred in association with the May 1980 earthquakes on numerous faults in the vicinity of Mammoth Lakes (see accompanying paper by Taylor and Bryant).
2. Additional investigations will be made to determine which faults should be zoned under the Alquist-Priolo Act and how to delineate Special Studies Zones for the regulation of development by Mono County and other permitting agencies. Preliminary Review Maps will be issued in the near future for review 6 months before Official Maps are issued. Once established, Mono County and other governmental agencies will need to regulate development within the established zones.
3. Future fault rupture, largely in the form of differential settlement, may continue across the faults for months or even years. Additional faulting (probably minor) also may occur along faults not previously observed to be active as the ground surface adjusts to new subsurface changes. Surface rupture also may occur in association with future moderate to large earthquakes. New construction

should avoid the active faults, as well as the closely associated problems of downhill movement of surficial material on fault scarps.

4. New information documenting new or overlooked fault-rupture should be brought to the attention of this writer.

ACKNOWLEDGEMENT

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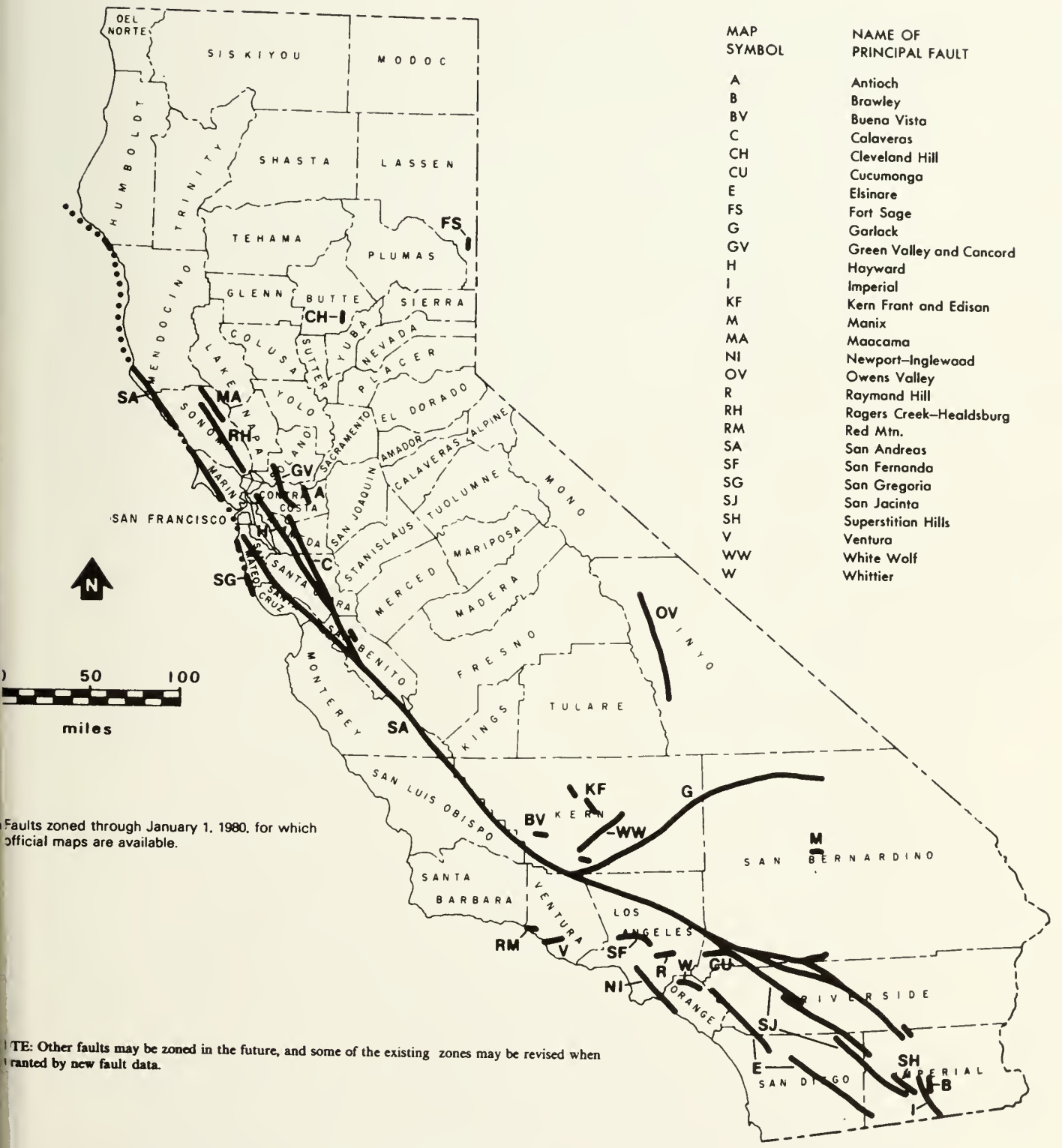


Figure 1. Faults in California zoned for special studies under the Alquist-Priola Special Studies Zones Act of 1972.

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SURFACE RUPTURE ASSOCIATED WITH
THE MAMMOTH LAKES, CALIFORNIA
EARTHQUAKES OF MAY 25 AND 27, 1980

By
Gary C. Taylor and William A. Bryant

MAP EXPLANATION

Linear crack zone apparently due to faulting, but commonly enhanced by shaking; solid where continuous, dashed where discontinuous. Cracks with vertical offset along scarp indicated with ball and bar on downthrown side. Number indicates locality description (see tabulation in text).

Fault location compiled from published literature and aerial photo interpretation by authors. Solid where well defined, dashed where less well defined, dotted where concealed or inferred; query indicates additional uncertainty. Ball and bar indicates downthrown side of scarp.

Crack zone due to slumping of soft sediment in meadows and valleys; apparently not fault related. Hachures on downthrown side.

Minor cracks due to slumping or landsliding.

Areas where fault traces mapped by Rinehart and Ross (1964) or Bailey and Koeppen (1977) were inspected for new cracks after the May 1980 events and no new cracks were observed.

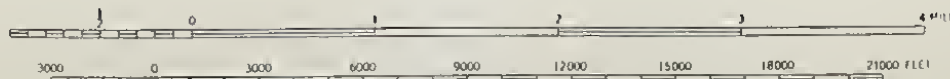
Location, number, and orientation of photo used in accompanying text.

ACKNOWLEDGEMENTS

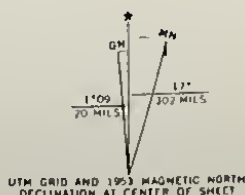
This compilation has incorporated field data from the following CDMG personnel: Earl W. Hart, Trinda L. Bedrossian, James E. Kahle, and Richard D. McKinnin; and from the following U.S. Geological Survey personnel: M.M. Clark, J.C. Yount, P.R. Vaughan, J.C. Illsley and E.J. King. These contributors are gratefully acknowledged.

Topographic Base By U.S. Geological Survey
Mt. Morrison 15' Quadrangle

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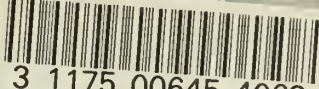
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